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Abstract

OPERATIONAL CHARACTERISTICS OF A LIQUID NITROGEN POWERED AUTOMOBILE

by Peter D. Vitt

Chairperson of the Supervisory Committee:

Professor Emeritus Abraham Hertzberg

Department of Aeronautics and Astronautics

The University of Washington is studying a zero-emission vehicle concept, the cryogenic automobile. This propulsion concept uses a cryogenic liquid as its energy storage medium, and offers environmental and economic benefits over current alternative vehicles. The University of Washington is investigating the use of nitrogen, stored in liquid state, as the working fluid in an open Rankine cycle. The liquid nitrogen is first pressurized, then vaporized and superheated in an ambient air heat exchanger. The resulting high pressure gas is injected into an expander which produces the system's motive work. The spent, low pressure gas is exhausted to the atmosphere. A test vehicle was assembled and is being used to learn about liquid nitrogen propulsion. The road performance of cryogenic automobiles was predicted using a mathematical model. The model can be modified for a variety of design choices and configurations. The performance of the test vehicle validates the heat exchanger concept and directs future efforts toward development of a better nitrogen expansion motor. This thesis describes the construction and operation of a liquid nitrogen powered automobile. Operational characteristics like road performance, maintenance, cost, and environmental impact are also explored.

OPERATIONAL CHARACTERISTICS OF A
LIQUID NITROGEN POWERED
AUTOMOBILE

by

Peter D. Vitt

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Aeronautics and Astronautics

University of Washington

1997

Approved by × Abraham Hertzberg
Chairperson of Supervisory Committee

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to Offer Degree Aeronautics and Astronautics

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Master's Thesis

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Nomenclature

Symbols

a = vehicle acceleration (m/s^2)

A = frontal area (m^2)

C_D = coefficient of drag

d = wheel diameter (m)

D = aerodynamic drag (N)

f_r = rolling resistance coefficient

F_r = rolling friction (N)

g = acceleration of gravity (m/s^2)

m = vehicle mass (kg)

$\dot{m}$ = mass flow (kg/s)

r = wheel radius (m)

RPM = revolutions per minute

T = motor torque (Nm)

T = temperature (K)

V = velocity (m/s)

ρ = density of the air (kg/m^3)

θ = road angle from horizontal (rad)

Acknowledgments

The author wishes to thank Matthew Arbogast, Leland Cheung, Helene DeParis, Chris Hall, Brian Holm, Greg Lipski, William Lowe, Neil Martin, Ernesto Manjares, Russell Niemann, Dennis Peterson, and John Williams for their assistance in setting up the experimental facilities, constructing the vehicle, and performing the experiments. Thanks are also due to Professors Adam Bruckner and Tom Mattick, and Doctor Carl Knowlen for their encouragement and thoughtful comments. This research was funded by the Department of Energy under grant number DE-FG06-95ER12172.

I. Introduction

Cars are bad for the environment. In half of the world's cities, tailpipe emissions are the single largest source of air pollution. Worldwide, automobiles account for half of the oil consumed and a fifth of the greenhouse gases emitted. This situation is not expected to improve, as the number of cars and light trucks in the world – over 500 million – is expected to double in the next thirty years. Most of this growth will occur in developing countries which have little or no emission controls.[1] According to the U.S. Environmental Protection Agency (EPA), more than half the U.S. population lives in areas where pollution levels exceed established air quality standards.[2] In urban areas of southern California, vehicles account for over 50% of the air pollution emitted.[3]

A wide range of work is being done in an attempt to reduce the effect of automobiles on the environment. California and other states have enacted laws attempting to force the sale of zero emission vehicles. In September of 1990, the California Air Resources Board enacted the Low Emission Vehicle (LEV) program.[4] The LEV program established several categories of emission standards for cars and light trucks. The most stringent of these categories was for the zero-emission vehicle (ZEV). By 2003, each of the seven largest automobile manufacturers must offer a fleet of cars in California with 10% meeting the ZEV criteria. This mandates about 110,000 cars per year without any tailpipe pollutants.[5] Similar mandates have also been adopted by New York and Massachusetts.

There have been a variety of approaches to create practical ZEVs for commercial sale. The most effort has been in the field of chemical battery powered cars, but others have focused on fuel-cells, flywheels, or more exotic power sources like thermal photovoltaic energy conversion[6]. General Motors' EV1, powered by electrochemical batteries, is currently being leased to consumers in California and Arizona. Toyota and other major automakers are also beginning to offer cars powered by nickel-metal hydride batteries.[7]

Electric cars are the only zero-emission vehicle type widely available to the public, but they are not selling well. This is primarily because of limited range, poor performance, slow recharge, and high battery replacement cost. All of these issues can be traced directly to the limitations of electrochemical energy storage methods, particularly lead-acid batteries. Lead-acid remains the dominant technology in the electric vehicle market, but these batteries only exhibit energy densities in the range of 108-144 kJ/kg. This compares with about 10.1 MJ/kg for gasoline, assuming an overall thermal efficiency of 25%.[8] Lead acid batteries can take hours to recharge and must be replaced every 2–3 years.

Electric cars, though they are ZEVs, would not necessarily be a large scale environmental solution. Lead-acid and other batteries contain high levels of hazardous substances like lead, nickel, phosphorus, and sulfur. This raises the specter of increased heavy metal pollution, were a lead-acid powered electric fleet ever to come to pass. Despite claims of environmental control of heavy metals, it is estimated that about 7% of lead is released into the environment during processing and manufacturing.[9] This leads to a dangerous situation with the number of automobiles on the road at 500 million and climbing. The environmental effects of large-scale mining, production, and disposal of different types of batteries have not been adequately addressed.

Electric cars, and other alternatives, suffer from further disadvantages. Batteries and flywheels suffer from material cost problems. Lithium-ion batteries, considered by many to be the third-generation solution, must also contend with cost and demonstrate their safety to a wary public. The special materials and processing necessary to fabricate these systems drive costs up. For example, the replacement cost of a battery pack can exceed the cost of the rest of the car; battery life cycle ranges from 2-6 years. There are also safety problems with some of these devices, including the possibility of explosion during overcharge or excess use. Batteries are potentially dangerous in crashes due to their density and hazardous materials (like liquid electrolytes or molten sodium). Flywheels have a tendency to catastrophically fail when disturbed, flinging broken pieces outward.

Overall vehicle performance will be the overriding factor determining the success of an alternative vehicle concept. During a 1997 J.D. Power and Associates survey titled "Electric Vehicles: The Consumer Perspective," American drivers described numerous factors they felt were important in determining which vehicle to purchase. [10] Such factors included everything from cost to styling, but there was no reference to environmental impact at all. Tim Gohmann, director of custom research at J.D. Power and Associates, put it more succinctly: "The true success of the EV will be based on its performance as a vehicle, not as an environmental solution."[11] It is reasonable to assume the same argument applies to all alternative vehicle concepts.

A different energy storage medium will be required to make ZEVs the *non-mandated* automobile choice of the car-buying public. If certain technical challenges can be overcome, that energy storage medium may well be liquid nitrogen. Since 1993, the University of Washington has been attacking the technical challenge of building and operating a vehicle powered by liquid nitrogen.[12] Issues pertaining to frost-free heat exchanger performance, cryogenic equipment, cycle analysis, quasi-isothermal expansion, vehicle configurations, and component performance are being investigated.

This thesis describes the fundamental concepts of cryogenic automotive propulsion. This includes the thermodynamic theory, the individual system components, the production of liquid nitrogen, and infrastructure considerations. The design, analysis, fabrication, and testing of a liquid nitrogen powered test vehicle is discussed in detail. Also discussed, are lessons learned and technical issues which must be addressed before a commercially viable production vehicle is produced. Finally, conclusions and recommendations for future research are presented.

II. Cryogenic Automotive Propulsion

The cryogenic automobile is a unique alternative propulsion concept. The cryogenic automobile utilizes the thermodynamic potential between the ambient atmosphere and some cryogenic medium. The difference between this and conventional automobile propulsion methods can be easily seen in Figure 1. Different storage material choices and energy conversion schemes allow many design options. Potential cost, safety, and environmental benefits add to the attractiveness of this propulsion concept. Finally, an infrastructure to provide large amounts of liquid nitrogen has the possibility of significantly reducing the amount of atmospheric greenhouse gases.

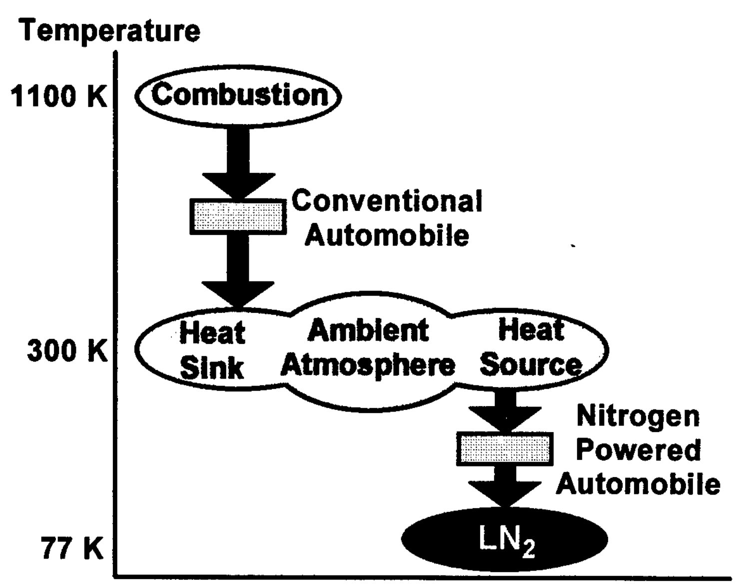

Figure 1: Heat Engine Illustration.

Many different approaches are available to utilize the energy stored in a cryogenic medium. Thermodynamic standard power cycles offer obvious options. A few possible cycles include: the Brayton cycle, the Rankine cycle, two- or three-fluid topping cycles, and even employing a hydrocarbon-fueled boiler for superheating beyond atmospheric temperatures. Further design options include adding reheat or deciding between open or closed systems. Alternatively, the temperature difference might be exploited using a thermoelectric power system.[2] Any of a large number of propulsion and alternative energy

storage methods could be combined with cryogenic energy storage to power a hybrid automobile.

The performance of any cryogenic propulsion system will be highly dependent upon its storage medium. The first decision is what state the material should stored be in. Possible options include a two-phase constant temperature reservoir, a single phase variable temperature storage medium, or a two-phase variable temperature medium. A recent paper discussing cryogenic energy storage points out the benefits of using low-mass gases like He, Ne, H_2, N_2, and air in two-phase cryogenic reservoirs.[13] Using Carnot efficiency, these substances offer the possibility of storing between 0.72 and 6.5 MJ/kg. Liquid nitrogen and liquid air are the most attractive for cold thermal storage because they're a essentially inexhaustible and readily available. Liquid nitrogen and liquid air also have considerable safety and environmental benefits, which will be discussed in greater detail later.

COST, SAFETY, AND ENVIRONMENTAL BENEFITS

Cost is a significant deterrent to public acceptance of most alternative vehicle concepts. Using an open Rankine cycle approach with liquid nitrogen or air could actually reduce the consumer cost of automobile use compared with gasoline powered cars. A liquid nitrogen system has the potential of delivering energy at a fuel cost of only about 60 cents/MJ, using the current commercial price for liquid nitrogen.[13] Assuming a realistic vehicle energy efficiency and using the current price of electricity, an operating cost of 6.2 cents/mile can be achieved.[2] This is competitive, at current technology levels, even with gasoline powered cars. A typical gasoline powered automobile costs roughly 5 cents/mile to operate in the United States. For comparison, General Motors' EV1 costs approximately 13 cents/mile to operate when battery replacement costs are included.[14] Additionally, the lack of emission controls and exotic materials would keep cryogenic vehicle prices low. Next-generation nickel-metal-hydride batteries contain significant

amounts of expensive materials like vanadium, titanium, zirconium, chromium, cobalt, and manganese.[15]

Liquid nitrogen powered automobiles offer many safety advantages over electric vehicles or gasoline powered cars. A liquid nitrogen system would contain no toxic, corrosive, or explosive chemicals. Spilt fuel would not be poisonous or linger at a crash site. The fuel tank is necessarily double walled for insulation, making it a likely candidate for absorbing energy during an impact.[16] Much is also known about the properties and behavior of common engineering materials at cryogenic temperatures; this adds an extra margin of safety.[17] Contrast these properties with the dense "battering ram" which most electric vehicle battery packs will become upon impact. There is a slight possibility of frostbite or asphyxiation with a liquid nitrogen system in a crash, however, there would be no low frequency magnetic field emissions or other hazards, like those sometimes encountered with electric vehicles.[13]

Using liquid nitrogen or liquid air allows the use of an open thermodynamic power cycle. For an open cycle, the exhaust would, at worst, be a low pressure nitrogen gas released directly into the atmosphere. Since nitrogen gas is the only emission, these cryogenic automobiles easily meet California's ZEV guidelines.[18] Other environmental benefits stem from an avoidance of using heavy metals like lead and nickel for batteries, as well as the sulfuric acid or potassium hydroxide used as electrolytes which could pose problems. A dramatic increase in mining, refining, and disposal of these materials for an electric car industry would also pose a significant threat to the environment. Heavy metals from mine tailings and disposal sites which get into the water supply cause significant health problems. Even though near-term production of liquid nitrogen would use the electrical power grid, commercial electrical power plants are generally cleaner than automobiles.[19] The next section details an added possibility which could actually have a positive effect on our atmosphere.

LIQUID NITROGEN INFRASTRUCTURE AND PRODUCTION

Having a liquid nitrogen infrastructure in place is crucial for the cryogenic automobile to become a mass-produced vehicle. Yet that infrastructure will not appear until a large market demand exists. This stumbling block is as critical as any technical difficulties involved with the performance of the vehicles themselves. Liquid nitrogen is currently produced on large scales for industrial, institutional, military, aerospace, and medical applications; however, it is not distributed widely like electricity, gasoline, and diesel fuel.

Several options are possible for the distribution of liquid nitrogen. Currently, liquid nitrogen is most commonly trucked and occasionally pumped through short pipelines. A more ambitious approach would be piping it through insulated jackets wrapped around superconducting power transmission lines. A more subtle distribution option is not to transport it at all. Installing a small-scale liquid nitrogen production facility at a filling station has many advantages, including an established retail system and using the local power grid for electrical power. The economics of distribution require further study.

Large scale liquid nitrogen production has its advantages as well. Figure 2 illustrates a concept in which the nitrogen liquefaction process is driven by a natural gas-fired power plant. Rather than using ambient air for the "feedstock," the liquefaction plant uses the turbine exhaust gas. In the process of obtaining the nitrogen, oxygen (a marketable commodity) is also liquefied. Moreover, the carbon dioxide from the power cycle combustion process can be condensed from the exhaust stream. Large, stationary power plants are the most economically viable targets for CO_2 sequestration.[20] A modern combined-cycle gas turbine power plant can produce enough energy to liquefy up to 70% of its own exhaust – most of which is nitrogen – while freezing all of the CO_2.[21] This can then be disposed of in several ways less harmful to the environment than simply venting it to the atmosphere.[22,23,24] This process raises the possibility of creating a liquid nitrogen-based transportation infrastructure that produces no atmospheric CO_2 emissions, and is the subject of further study.

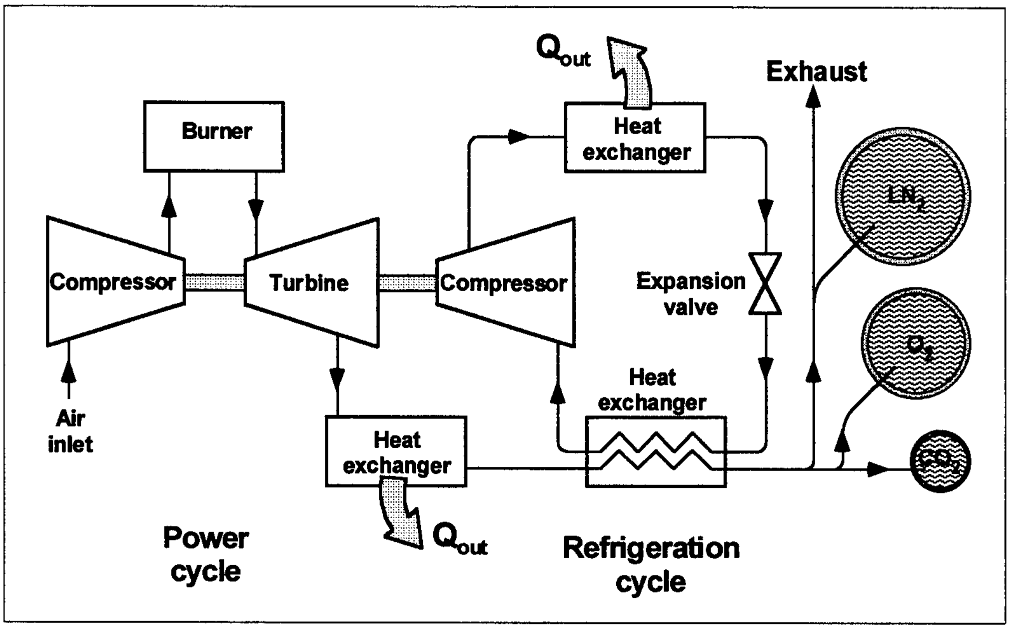

Figure 2: Proposed Nitrogen Liquefaction Process.

UNIVERSITY OF WASHINGTON PROPULSION CYCLE

Although the concept of a nitrogen powered automobile has been studied in the past,[25,26] a limited amount has actually been done in the way of demonstrating the concept on the road. This is primarily because one key technology has yet to be demonstrated: a frost-free liquid nitrogen vaporization and superheat system. In order to learn about the performance of propulsion systems and to demonstrate the viability of this new concept, the University of Washington undertook to produce a vehicle which runs on liquid nitrogen.[21]

With many different possible ways to utilize the thermodynamic potential, an easy cycle to implement was needed for the demonstration vehicle. The means chosen to demonstrate the potential of cryogenic automobile propulsion is shown in Figure 3. The open Rankine cycle was chosen because it was relatively easy to implement in terms of time, complexity, and cost. It begins with a tank of liquid nitrogen stored at 77 K and 1 bar. The nitrogen is pumped, as a liquid, to the system's working pressure. This high

pressure liquid flows into an economizer, which provides a frost-free pre-heat to the nitrogen by using the exhaust from the expander.

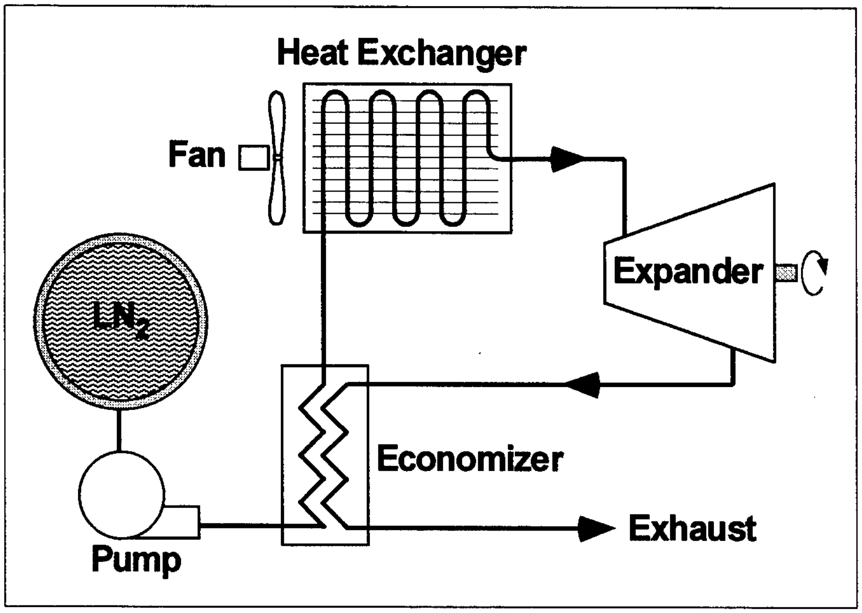

Figure 3: Liquid Nitrogen Propulsion System.

Once through the economizer, the vaporized nitrogen enters a heat exchanger, which uses the atmosphere for the heat source. The ambient air is drawn through the heat exchanger either by the motion of the vehicle or by a fan, depending on the operating regime. This heat exchanger must meet a variety or requirements. It has to operate across most of the spectrum of environmental and operating conditions without suffering the adverse effects of frost buildup.[21] It must also be robust enough to survive automotive use for a long period of time and be as lightweight and inexpensive as possible.

Upon leaving the heat exchanger, the working fluid is a high pressure, near-ambient temperature gas. It is injected into the expander which provides all of the motive work for the system. The expander can take a variety of forms, combining multiple stages and reheat with either a positive displacement or turbine engine. Because of it's immersion in a relatively warm environment, this expander offers the possibility of quasi-isothermal operation.[27] Following expansion, the low-pressure exhaust is warm enough to be used in an economizer, where it preheats the incoming liquid, before finally being vented to the

atmosphere. It's use in the economizer has the primary benefit of being a moisture-free gas, so it reduces the frosting concerns of the heat exchanger.

The temperature-entropy diagram for the open Rankine cycle, operated at critical pressure, is shown in Figure 4. Labels 1-2 indicate the pumping process. Because pressurization is occurring in the liquid phase of the fluid, the work required is small in comparison with the available work. Process 2-3 is the pass through the economizer and heat exchanger. Processes 3-4 and 3-4' are the isothermal and adiabatic modes of expansion, respectively. If the shaded area represents the available specific work in the cycle, then these two processes provide the upper and lower limits to the expander's performance. Process 4-1 (or 4'-1) is the liquefaction stage. This occurs remotely at an air processing plant.

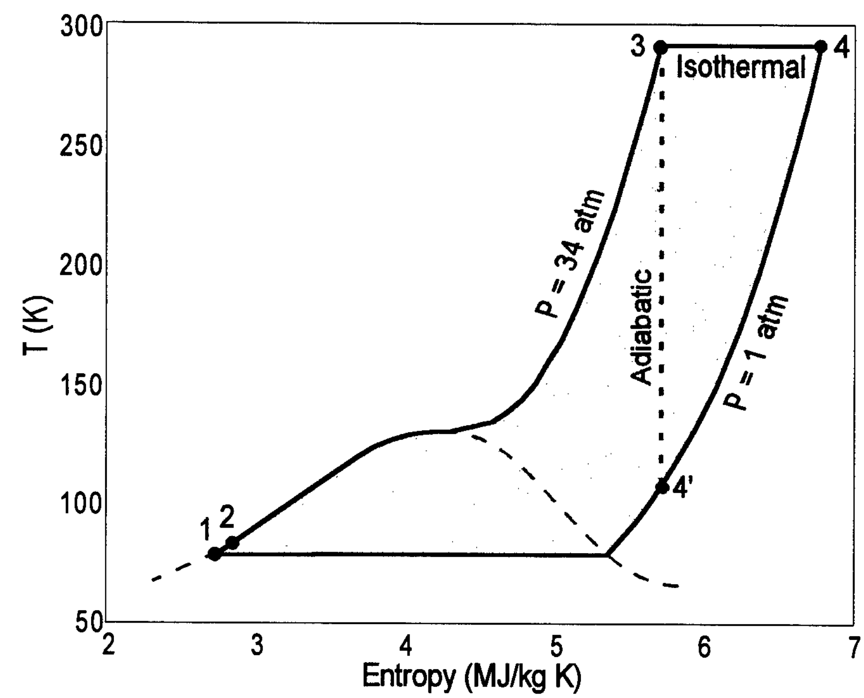

Figure 4: Temperature-Entropy Diagram for the Open Rankine Cycle.

Figure 5 and Figure 6 show how a liquid nitrogen based propulsion cycle fares against the various electrochemical storage media mentioned earlier. Specific energy is a useful figure of merit because it correlates closely with range. Energy density also helps

determine the physical size of the useable space inside a vehicle. Even the next generation nickel-metal hydride battery only matches the performance of the isothermal open Rankine cycle for specific energy. Additionally, the open Rankine is not the highest performing cycle available. By adding a methane topping cycle, about 504 kJ/kg can be achieved.[28]

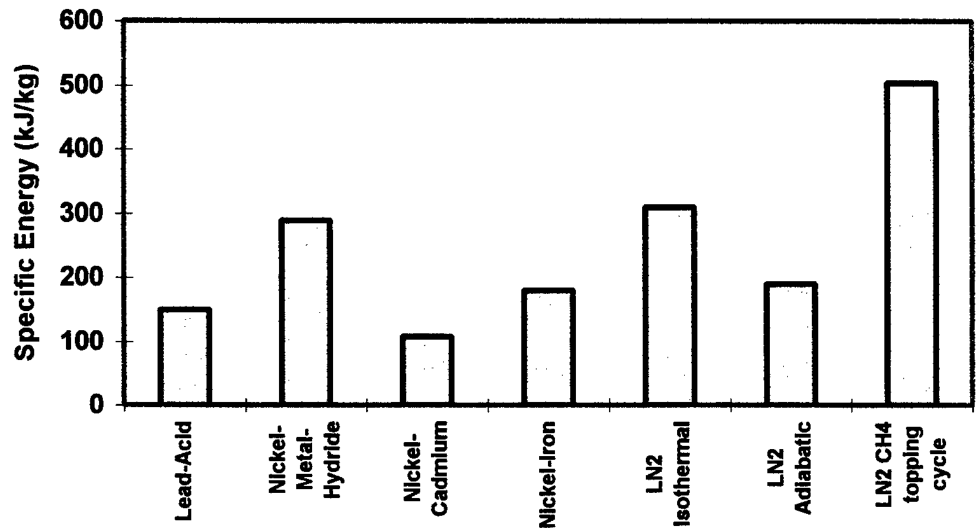

Figure 5: Specific Energy for Various Energy Storage Media.

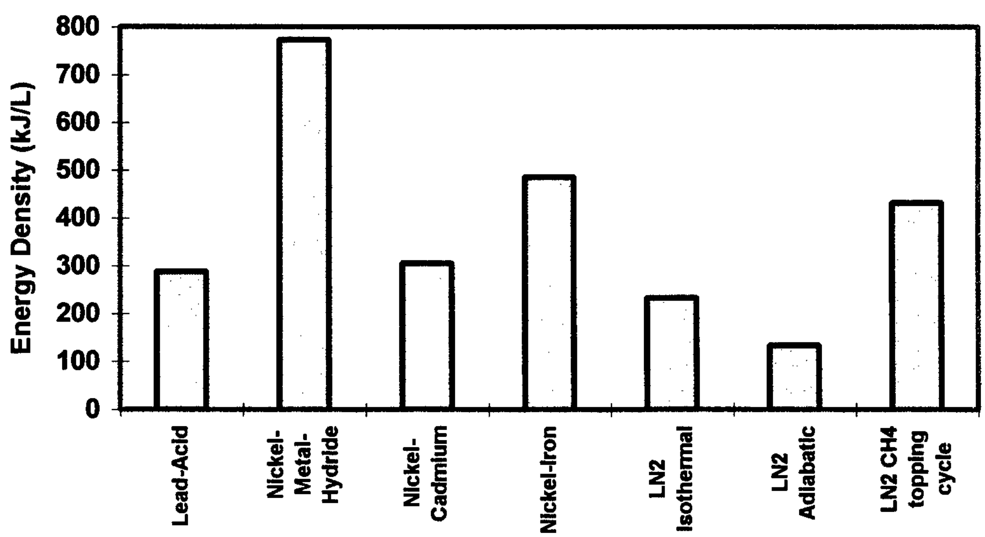

Figure 6: Energy Density for Various Energy Storage Media.

Comparisons of specific energy and energy density provide only a glimpse of how well a vehicle will perform. As previously mentioned, overall performance will determine how a vehicle is treated by the car-buying public.

III. LN2000 Design

OBJECTIVES

In order to further study cryogenic automobile propulsion, the University of Washington designed and assembled the LN2000 vehicle. The car uses liquid nitrogen as it's only propulsive fuel. The LN2000 vehicle was built to validate and test the design of an innovative frost-resistant nitrogen vaporization system.[28] Lessons can also be learned about the construction and operation of this new class of automobiles. The car serves as a rolling test-bed and proof-of-concept for cryogenic automobiles. At the time the project was undertaken, no cryogenic automobile had ever been successfully built, to the author's knowledge.[29]

As a test-vehicle, the LN2000 was built as quickly and inexpensively as possible and was not designed to compete with commercially available vehicles in terms of performance. To serve its purpose, the car must able to drive under it's own power and allow testing of the onboard heat exchanger. LN2000 must also demonstrate the advantages of cryogenic automobile propulsion over electric cars; namely, it should be refueled quickly, be simple and easy to maintain, and contain no expensive or environmentally damaging materials. The car is designed to run in all types of weather, climb hills, and operate with a minimal support staff. In order to help make good design choices, the performance of various configurations was modeled. The process used to predict LN2000's performance is described in Chapter IV.

VEHICLE DESCRIPTION

The LN2000 vehicle is built around a 1984 Grumman-Olson Kubvan, pictured in Figure 7. This model vehicle was originally built for the US Postal Service and could be purchased with either a diesel or electric drivetrain. The vehicle which forms the basis for LN2000 was originally electric. It held a pack of 14 lead acid batteries with a total mass

of over 450 kg. The vehicle uses a right-hand drive 1984 Volkswagen Rabbit transmission. The car is constructed of a welded frame with riveted body panels and is made entirely of aluminum.

Figure 7: 1984 Grumman-Olson Kubvan.

The Kubvan was selected for the test-vehicle for several reasons. The interior volume available and simplicity of construction - flat sheet-metal body panels, aluminum frame, open interior - allowed for easy modification. Also, because it was originally designed to be electric, it operates without extra features like air conditioning and rear window defrosting. All lights and gauges are powered by a single 12 V lead-acid battery mounted under the hood. The battery is recharged externally between sorties.

The LN2000 equipment layout is shown in Figure 8. Most of the cryogenic plumbing is stainless steel, but the interior elements of the economizer are aluminum. The pressurization system uses both aluminum and stainless steel plumbing as well. Low pressure plumbing utilizes 19.1 mm (3/4 in) inside diameter rubber hose where possible. Each of the items labeled in the figure are described below.

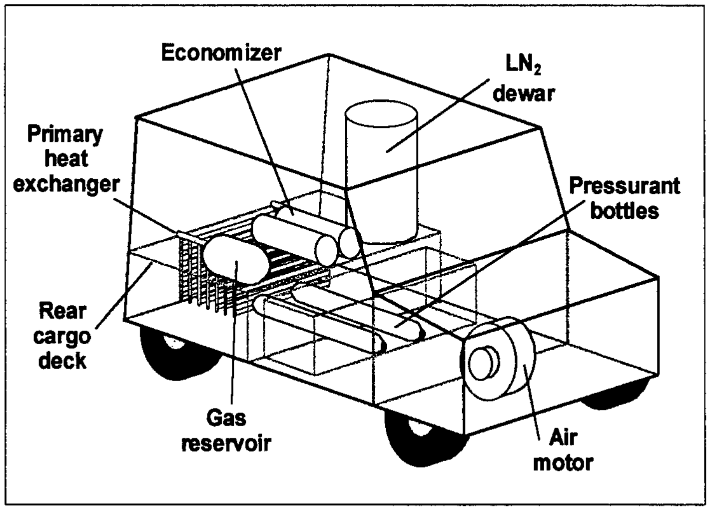

Figure 8: Schematic of Vehicle Equipment Layout.[28]

LIQUID NITROGEN STORAGE TANK

The dewar chosen for this application can hold 80 liters of liquid nitrogen at 24 bar with a boil-off rate of about 3% per day.[29] The primary protection against over-pressure is a relief valve connected to the internal vessel. This valve also serves as the bleed for the evaporated nitrogen, which is vented to the outside by a rubber hose. There are several other safety devices, providing multi-tiered protection against catastrophic rupture. The dewar is held in place at five attachment points: one on the roof, and four on the rear deck.

PRESSURIZATION SYSTEM

The pressurization system consists of two high-pressure nitrogen bottles stored under the rear deck of the Kubvan. This blowdown system has the advantages of mechanical simplicity and decreased cost; it's disadvantages include increased weight and volume. Each of the nitrogen bottles has a mass of 40 kg. The volume of gas required was calculated such that the pressurant tanks and the dewar get to within 44 psi of equilibrium just as the last of the liquid nitrogen is drained out. The pressurant tanks are initially filled to a starting pressure of about 2000 psi. This is regulated down to the system pressure of

350 psi before being injected into the dewar. The hardware required for filling both the pressurant bottles and the dewar is attached to the vehicle.

ECONOMIZER

The economizer is actually a pair of shell-and-tube heat exchangers, as shown in Figure 9. These compact, lightweight heat exchangers operate in parallel, with the shell-side fluid being the exhaust gas from the expander. The shells are made of high-density polyethylene and the internal tubes are 6.4 mm diameter seamless aluminum tubing. Each tube makes five passes through the interior of the shell. Internal baffles direct the shell-side gas across the tubes in a cross-flow pattern. When operating at maximum mass flow, ~300 g/s, the economizer is designed to bring the liquid nitrogen to a quality of about 75%. This represents approximately one quarter of the total enthalpy change the nitrogen will experience before being injected into the expander. The design and construction of both the economizer and the heat exchanger are described in detail in another work.[28]

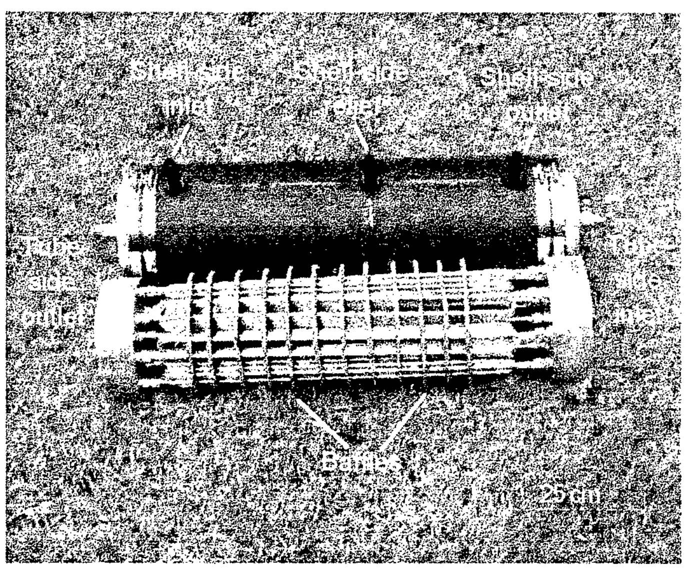

Figure 9: Economizer Units With and Without Shell.[28]

AMBIENT-AIR HEAT EXCHANGER

The ambient-air heat exchanger is made up of 45 finned-tube elements. These elements are manifolded together, as shown in Figure 10, to make a staggered array of tubes in crossflow with the incoming air. The first bank of six tubes is a superheater section whose elements do not have the internal ducting. The primary elements are three-pass tubes, with a design which makes frost-free operation possible. The outer finned tubes are made of copper and the internal plumbing is of bronze. The air is propelled through the heat exchanger by either the motion of the vehicle or the two 100 W ducted fans hung from the rear of the vehicle. The fans are powered by a dedicated 12 V lead-acid battery mounted in the rear of the vehicle. This battery is recharged externally between tests. The air inlet consists of an aluminum scoop slung underneath the vehicle.[28]

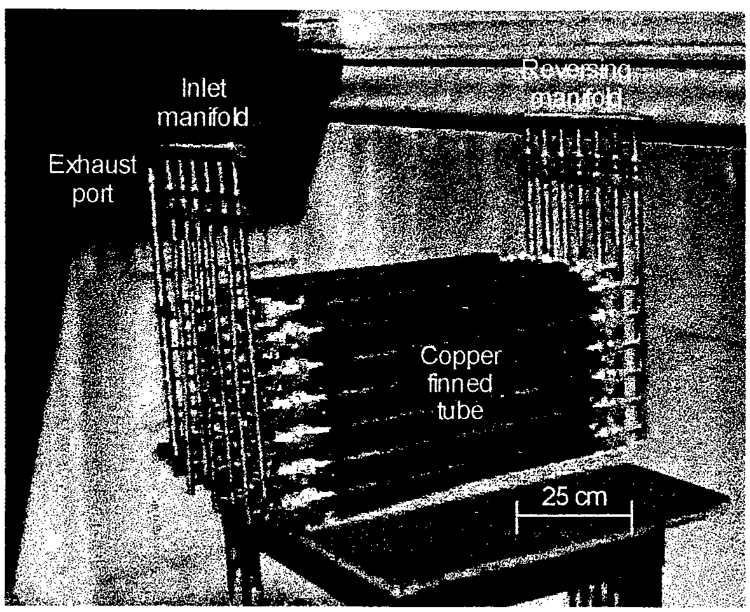

Figure 10: Ambient-Air Heat Exchanger Assembly.[28]

EXPANDER

The expander installed in the LN2000 vehicle is an 11 kW, radial piston air motor made by Cooper Power Tools. This motor, pictured in Figure 11, has a cast-iron block with five 7.5 cm cylinders. It was originally used for raising and lowering the anchor

onboard a ship. The motor is not designed for efficient use of compressed air, nor is it optimized for automotive use. Each cylinder holds a steel piston attached to the single-throw crank shaft by a connecting rod. Lubrication is maintained by splash and by an oiler located near the gas inlet. The oil used in the both the motor and transmission is SAE 85W140 heavy hypoid gear oil. The motor is attached to the front-wheel drive, 5-speed manual transmission by a custom-made aluminum gear-box. The output shaft of the motor drives a 15.24 cm diametral pitch (DP) spur gear. The input shaft to the clutch assembly has a 7.62 cm DP spur gear, giving a 1:2 speed ratio through the gear box. The running gear is from a 1984 Volkswagen Rabbit and is right-hand drive.

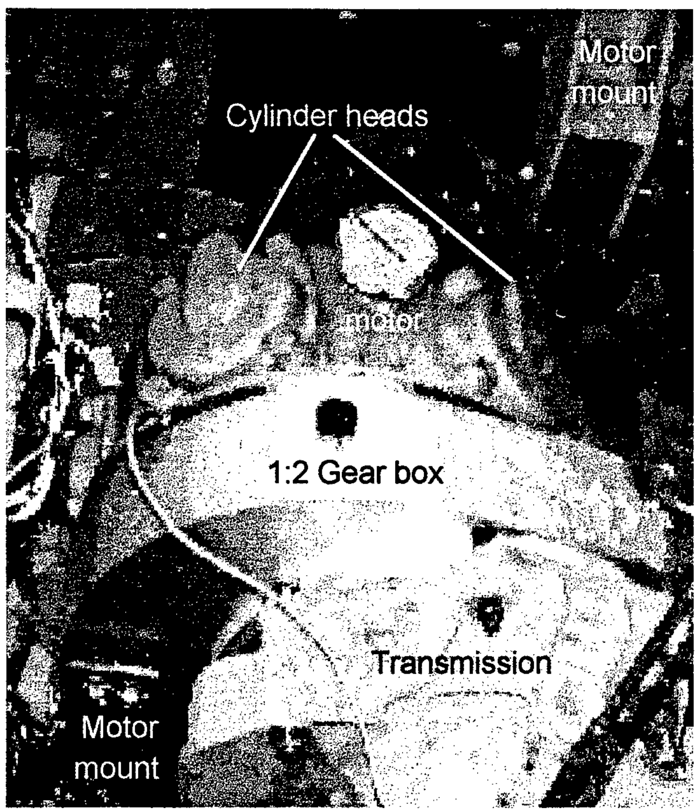

Figure 11: Motor and Transmission Assembly.[28]

Many lessons were learned in the course of the fabrication of this vehicle. The vehicle itself was an excellent choice for retrofit because of its available volume and simple

construction. The vehicle components were either fabricated at the University of Washington, or purchased off the shelf. The components produced in the Aeronautics and Astronautics machine shop include: the economizers, the motor-transmission coupling, and the heat exchanger elements and final heat exchanger assembly. The heat exchanger manifolds were welded in the Department of Chemistry machine shop. The largest cost associated with fabrication and assembly was the required man-hours. Each component was basically hand-made and unique. For a mass-produced vehicle more care would be taken in design to make the parts easy to produce. For example, the finned-tube heat exchanger elements were made of copper instead of aluminum because the manufacturing plant was doing a run of copper at that particular time. The assembly of each individual heat exchanger element and the internal tubing for the economizers was tedious and slow. Future designs should incorporate easier to assemble pieces for less expensive production.

IV. Performance Prediction

The author developed a computer program which predicts the performance of a cryogenically powered automobile in different driving conditions. This facilitated the construction of a liquid nitrogen powered test vehicle by enabling better and more timely design choices. The computer model predicts the road performance and range of a vehicle using various configurations and components. One major design goal was to maximize the car's road performance while ensuring it could be built quickly and inexpensively. The modeling process was made more difficult by a lack of information about key components, but reasonable assumptions were made. An effort was made to alter the system design in order to maximize the predicted range and acceleration of the vehicle based on the model's predictions. The computer program was also modified to predict performance of improved vehicles. The performance of the same chassis with better motors installed was first predicted. Then, the model was used to predict the performance of a purpose-built vehicle, with better plumbing and an efficient motor.

MODELING PROCESS

The computer model uses an iterative loop which incrementally calculates performance data based on the previous time step's results. It was written in the Matlab programming language. The length of each time step can be set by the user. The input for each iteration is the desired vehicle speed, which can be taken from a variety of different driving cycles. The most often used driving cycles include maximum acceleration, maximum speed cruise, and an urban driving cycle provided by the EPA. The algorithm, pictured in Figure 12, compares current velocity with desired velocity, determines the desired acceleration, and then calculates the necessary wheel torque for that desired acceleration. The model determines the correct gear for the vehicle's speed and then finds the current motor RPM. A motor torque versus pressure curve fit at that RPM allows the program to determine the necessary gas pressure. RPM and gas pressure determine the

mass flow through the motor. After the actual motor torque is calculated, actual vehicle acceleration is found and a new current velocity value starts the iteration again. Distance traveled and total mass flow are found by integrating velocity and instantaneous mass flow over time. The model continually updates vehicle mass as nitrogen is consumed. The Matlab code is found in Appendix A.

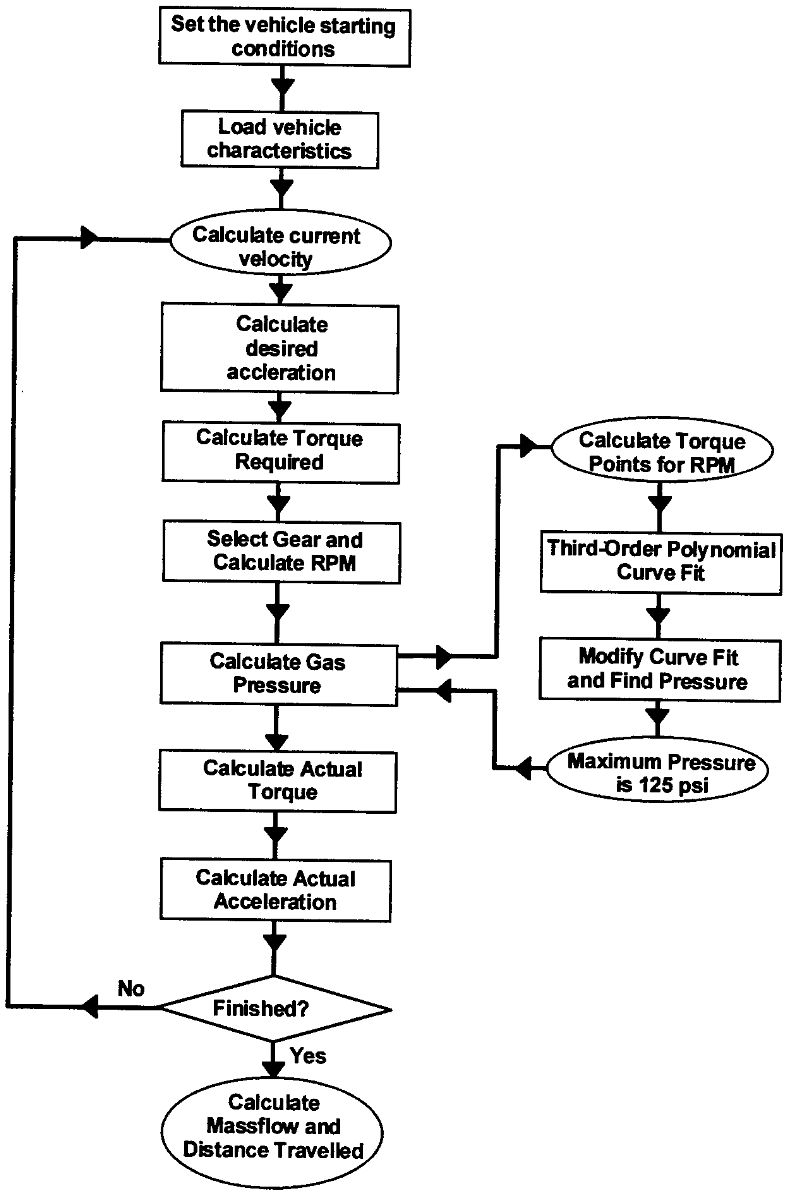

Figure 12: Performance Prediction Algorithm.

The performance model's accuracy depends on several simplifying assumptions. The first set of assumptions (or approximations) has to do with the physical properties of the vehicle. These properties are stored in a subroutine called *paramsd.m* which is also found in Appendix A. The total mass of the vehicle is estimated to start out at 1430 kg, using the dry weight of the vehicle and estimating the mass of components added (including the liquid nitrogen and occupants). The amount of liquid nitrogen stored in a full tank is estimated by using the NIST database to determine the density of the saturated liquid at operating pressure.[30] Transmission gear ratios used in the program are standard for the Volkswagen transmission which is installed in the LN2000. Their values are stored in the subroutine *trani3.m* (Appendix A).

Simple mathematical models for aerodynamic drag and rolling friction give estimates for the actual values. Aerodynamic drag is approximated by the following equation:[31]

$$D = \frac{\rho A C_D V^2}{2} \tag{1}$$

The LN2000 cross-sectional area is approximately 2.4 m^2 and the coefficient of drag is estimated at 0.8, which is comparable to those measured for vehicles with the same basic shape. Rolling resistance is defined as the drag force on the vehicle excluding aerodynamic effects.[32] The rolling resistance can be estimated using another simple equation:[31]

$$F_r = f_r \cdot m \cdot \cos\theta \cdot g \cdot \left(1 + 10^{-3} V + 10^{-5} V^2\right) \tag{2}$$

Here the rolling resistance coefficient, f_r, is set at 0.013 for normal city driving and tire inflation pressure. The actual value of f_r will change with temperature, inflation pressure, road conditions, and velocity.[31,32] The angle the road makes with horizontal, θ, only comes into play for hill-climb tests. The aerodynamic drag and rolling resistance calculations correlated reasonably well with coast-down tests made with the vehicle.[14]

These two quantities can be combined to produce a predicted curve for road power versus velocity. This information is shown in Figure 13.

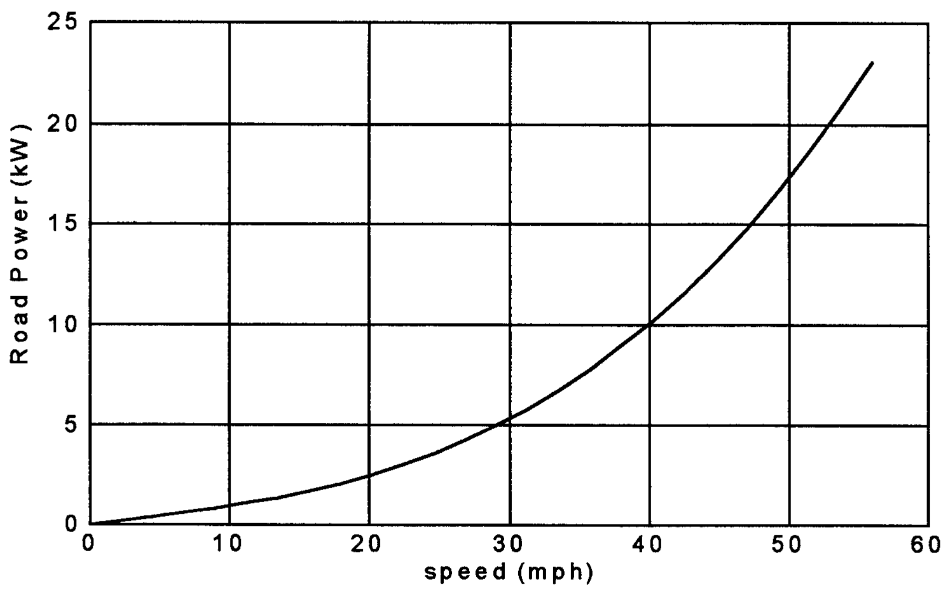

Figure 13: LN2000 Road Power Versus Speed.

The program uses manufacturer's data for the air motor to predict nitrogen consumption and motor torque. The data available consisted only of a plot of torque and power versus RPM, and a table listing various performance properties at maximum power (1070 RPM).[33] The manufacturer states a gas consumption of 348 SCFM (9.86 m^3/min) at maximum power for the MM motor. This information is used in a subroutine called *vdotd.m* (Appendix A) which provides a linear approximation of the volumetric flow rate through the motor at any RPM. The function *mdotd* then uses the volumetric flow rate and the density of the incoming gas, knowing pressure and assuming 288 K, to find the massflow.[30] This temperature was supplied by calculations simulating the performance of the heat exchanger.[28]

The motor RPM is determined by vehicle speed and the transmission gear selected. To approximate shifting, the computer model selects the correct gear to achieve maximum torque at the wheels at the current vehicle velocity. In order to design the shifting scheme,

vehicle velocity versus wheel torque was plotted for each gear as shown in Figure 14. A different shifting scheme was found for each simulated change in the motor transmission coupling gear ratio. Once the gear is selected, the motor RPM is calculated with the following equation where d is the front wheel diameter:

$$\text{RPM} = \left(\frac{V}{\pi \cdot d}\right) \cdot 60 \cdot \text{gear ratio} \tag{3}$$

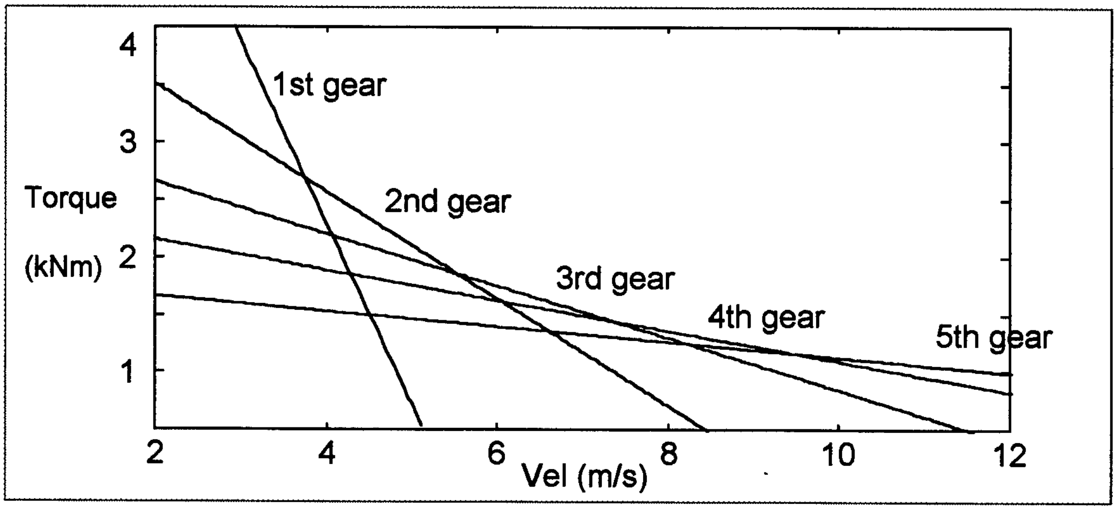

Figure 14: Wheel Torque Versus Vehicle Speed.[14]

Based on the plot supplied by the motor manufacturer, the program assumes a linear relationship between torque and RPM.[33] The motor is immediately set apart from traditional automotive engines by this linearly decreasing torque curve and parabolic power curve; a gasoline engine has a flatter torque curve and a power curve which generally increases with RPM over most of its operating range.[31,32] A specialized curve fit approximates the torque versus gas pressure curve at any given motor RPM. This allows the determination of the necessary input gas pressure for the desired motor torque. The curve fit is difficult because motor torque varies with both input pressure and RPM. First, data from the manufacturer's plot was linearly fit into a torque versus RPM curve for each of three different input gas pressures (70, 80, and 90 psig). One of these curves is demonstrated in Figure 15.

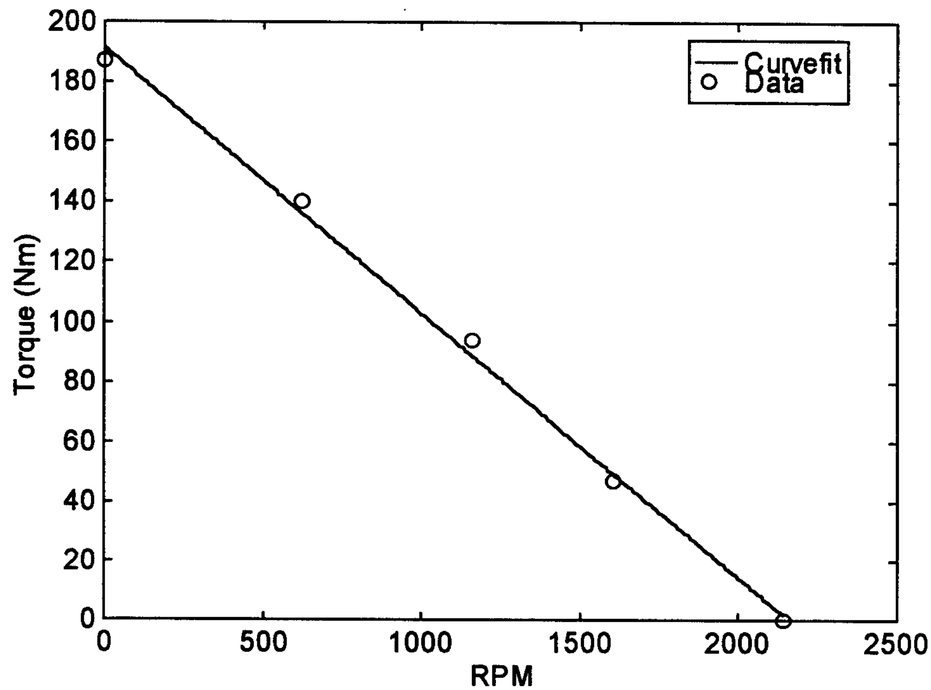

Figure 15: Torque Versus RPM at 90 psi.

Inside the iterative loop, three torque versus pressure points are calculated using the motor's current RPM and each pressure's torque versus RPM curve. The three points are combined with zero-zero to enable a third-order polynomial curve fit for pressure versus torque. To better follow observed air motor behavior, the curve fit is then modified to use the slope at 70 psi and continue in a straight line to the zero-torque axis. This can be seen in Figure 16. After calculating the curve fit, the model selects the appropriate input pressure, or 90 psi maximum, and calculates the torque supplied by the motor.

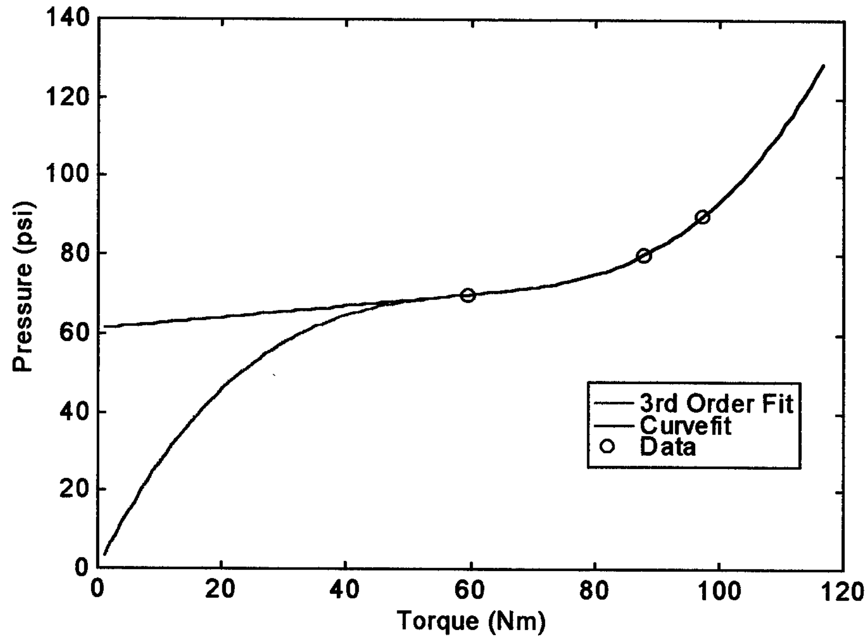

Figure 16: Pressure Versus Torque at 1070 RPM.

The program calculates vehicle acceleration using the torque produced by the motor at the selected pressure and RPM. The vehicle acceleration is found using equation (4).

$$a = \frac{1}{m}\left(\frac{T \cdot 0.85 \cdot \text{gear ratio}}{r} - D - F_r\right) \tag{4}$$

The motor torque is assumed to be transmitted to the wheels with 85% efficiency.[32] The gear ratio is a combination of the differential and particular gear selected, and m is the mass of the vehicle.

The Matlab model predicts the vehicle range for a variety of conditions. For a realistic city nitrogen consumption rate, an EPA approved Federal Urban Driving Schedule, pictured in Figure 17, was used. The urban driving cycle is designed for determining automobile gas mileage. The Kubvan will not travel the entire cycle on one tank because of its inefficient motor, so an average consumption rate for the whole cycle was used in conjunction with the size of the fuel tank to determine vehicle range.

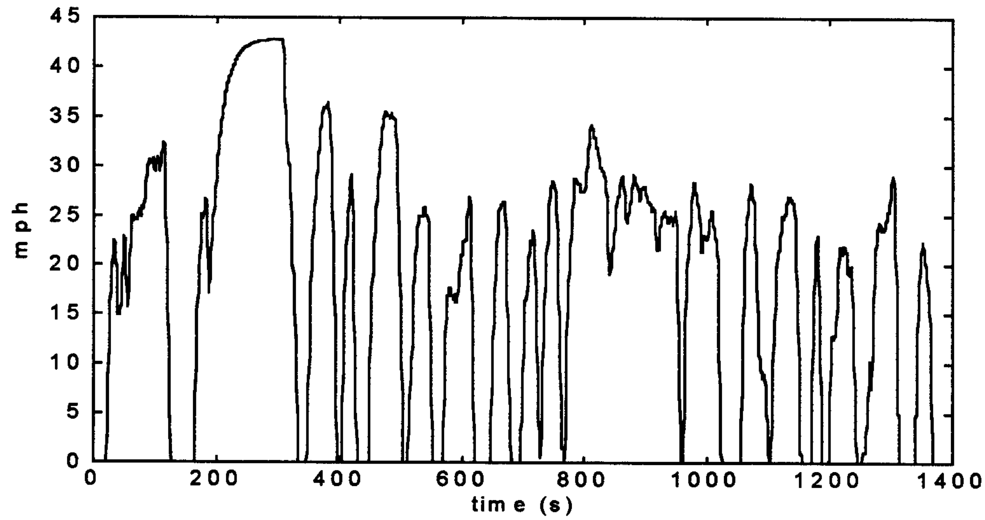

Figure 17: EPA Federal Urban Driving Schedule.[14]

PERFORMANCE PREDICTION FOR SYSTEM DESIGN

Once the basic vehicle behavior is modeled, the program allows changes in the configuration and the prediction of the effects of those changes on overall vehicle performance. The first question addressed was one of the most important to the operation of LN2000. The choice had to be made whether to construct a vehicle with a motor that directly drove the wheels, or a hybrid-electric car where the motor drove an alternator to charge a battery pack. The basic motivation behind the hybrid configuration was an anticipated increase in range because of the continually optimum operation of the air motor. On the other hand, a direct-drive configuration would be more simple, faster and less expensive to construct. Using results from the Matlab program, it was decided that while the direct-drive car probably wouldn't go very far or very fast, it would be enough to allow testing of the heat exchanger and demonstrate the feasibility of the concept.

The necessity of fabricating a coupling between the air motor and the car's transmission provided for another design option. Since mass flow is linearly related to motor RPM, it is possible to decrease motor RPM by changing the transmission

differential ratio. The performance model was used to predict a full range of possible gear ratios. The design choice became a balance between decreased LN_2 consumption and increased time to accelerate from rest to 30 mph. A gear ratio of 2:1 was found to offer the best overall performance. This change would effectively halve the differential ratio for the Kubvan's transmission and halve the motor RPM for any given vehicle speed. By incorporating the reduction gear in the motor coupling, the LN_2 consumption rate is 18% less than in the 1:1 configuration (using the Federal Urban Driving Schedule). The vehicle's acceleration will be adversely affected, but by adjusting the speeds where the vehicle shifts, 0-30 mph time increases only two seconds (9%). The vehicle's ability to climb a hill at 20 mph is also affected. The maximum angle of roadway LN2000 is predicted to be able to climb at 20 mph is decreased by 6%. With a 2:1 coupling, the LN2000 is predicted to be able to climb a 5.2% grade at 20 mph. These results are summarized in Table 1.

As previously discussed, the torque versus RPM characteristics of the MM motor differ from a conventional gasoline engine.[31,32] In an attempt to make best use of the linearly decreasing torque curve, a performance analysis was done with the transmission set in fifth gear. Not shifting gears decreases LN2000's predicted nitrogen consumption by 71%, but also slows the 0-30 mph time by 33 s (143%). While 23 seconds is poor, 56 seconds to go from rest to 30 mph is probably unsafe on public streets. Even with though it was designed for use with a gasoline engine, the Kubvan transmission will be useful to obtain the best possible performance. The strong correlation between engine RPM and consumption rate suggests selecting the highest gear possible while still obtaining the necessary acceleration. This will allow the vehicle to get the best possible mileage. These data can also be seen in Table 1.

Table 1: Predicted Performance of Various LN2000 Configurations.

	Final Configuration	1:1 Motor Coupling	5th Gear Only
Max. Range	3.73 km	3.07 km	6.36 km
0-30 mph	23 s	21 s	56 s
Max. Speed	38.6 mph	36.8 mph	36.6 mph
Hill-Climb at 20 mph	5.2% grade	5.5% grade	1.1% grade

The final configuration of LN2000 was based upon these predicted performance parameters. The final configuration is predicted to be relatively insensitive to increases in vehicle mass. If the total mass of the car increases by 143 kg (10%), range only decreases by 2.9%. On the other hand, for the same increase in vehicle mass, the 0-30 mph time increases from 23 seconds to 26 seconds (a 13% increase). These results are tabulated in Table 2. As in any automobile, vehicle mass should be minimized without sacrificing safety or propulsive efficiency. The predicted sensitivities allow some comfort in the ability to produce a working vehicle even if the total mass were to be larger than anticipated.

Table 2: Sensitivity to Vehicle Mass.

	Predicted Mass (1430 kg)	Heavy Vehicle (1573 kg)	Percent Change
Max. Range	3.73 km	3.62 km	-2.9%
0-30 mph	23 s	26 s	13%
Max. Speed	38.6 mph	38.0 mph	-1.6%
Hill-Climb	5.2% grade	4.7% grade	-9.7%

The Kubvan performance using the prototype LN_2 propulsion system has been calculated and is given in Table 3. The data for the table were calculated using EPA approved Urban and Highway driving cycles.

Table 3: Predicted LN2000 Performance.

	City Cycle	Highway Cycle	Maximum Speed *
Avg. Mass Flow (g/s)	87	175	184
Max. Mass Flow (g/s)	213	199	186
Consumption (kg/km)	10.9	10.6	10.7
Avg. Power (kW)	4.7	10.4	10.9
Max. Power (kW)	10.9	10.9	10.9

* At a top speed of 62 km/h (39 mph).

OTHER PERFORMANCE CONSIDERATIONS

When considering the performance of a test vehicle like LN2000, many factors must be taken into account. Foremost, the vehicle must allow for testing of the performance and responsiveness of the heat exchanger design. The car should also demonstrate the possibility of quick refueling for cryogenic vehicles. It must demonstrate an ability to run in extreme weather conditions like heat, cold, snow, rain, and high humidity. The vehicle concept was predicted to be low-maintenance, requiring only routine, inexpensive upkeep. It should be able to run for extended periods and under realistic conditions. The durability of the test vehicle should be excellent due to a lack of complicated or fragile components. It must also demonstrate the ability to drive in varying road conditions like potholes, gravel, and ice. In order to demonstrate the utility of the concept, LN2000 was built to test many of the conditions faced by a gasoline powered automobile.

Since it vehicle would not need to idle, the vehicle should perform almost as well in stop-and-go traffic as during "highway" tests at high speeds for long periods, as indicated in Table 3. The vehicle was predicted to actually perform best immediately after starting, or during the so-called "cold-start period." This is because it was anticipated that the thermal mass of the heat exchanger system and plumbing would serve to heat the nitrogen without even the help of the ambient air. Thus, unlike a gasoline powered car, a cryogenic vehicle should start out with it's best performance right at the beginning. The LN2000

was also anticipated to best typical battery powered electric vehicles whose performance decreases as the battery is discharged. The nitrogen system should perform as well using the last gallon of fuel as it did using the first gallon.

FUTURE VEHICLE PERFORMANCE

One objective of the project is to anticipate and demonstrate the future performance of cryogenic automobiles. The demonstration vehicle is not designed to be competitive at the dealerships with either electric powered or gasoline powered cars. A modified mathematical performance model predicts what more advanced vehicles could do, including an improved LN2000 with a better motor and a purpose-built vehicle with a third-generation expander.

The most obvious step in improving the performance of the LN2000 is to replace the existing motor with a higher efficiency, purpose-built expander. A better motor would make more efficient use of the available energy, as described in Chapter V. This prediction uses the information given in Figure 13, and builds upon the original mathematical model. The major problems with the LN2000 vehicle are in the area of expander efficiency and pressure delivery. The pressure delivery problems can be improved by installing a throttle designed for higher flowrates. It is anticipated that the vehicle will then be able to deliver 150 psi nitrogen gas to the motor at about 288 K. Assuming either ideal adiabatic or isothermal expansion, the performance of an upgraded LN2000 vehicle can be estimated.

The updated model, called *ddrivea.m* is found in Appendix B. This model uses the same basic programming structure as *ddrive.m*, but differs in a few key aspects. The first major difference is in the modeling of the power and torque versus RPM curves for the new motors. Based on the available literature for vane and piston-type air motors, a parabolic power versus RPM curve is assumed. For the purposes of this simulation, the next-generation motor is assumed to have a maximum power of 40 kW at 1358 RPM.

This figure was arrived upon by calculating the power necessary to provide a top speed in the neighborhood of 65 mph to the LN2000 vehicle. The power versus RPM curve is shown in Figure 18. This curve is calculated using a second-order polynomial curve fit in the subroutine *pcurvea.m*, also found in Appendix B. The torque for the motor may then be approximated using the motor's current RPM and power. To better simulate a real motor's starting torque, this is set at approximately 80% of the motor's stall torque. This effectively limits the motor to 450 Nm.

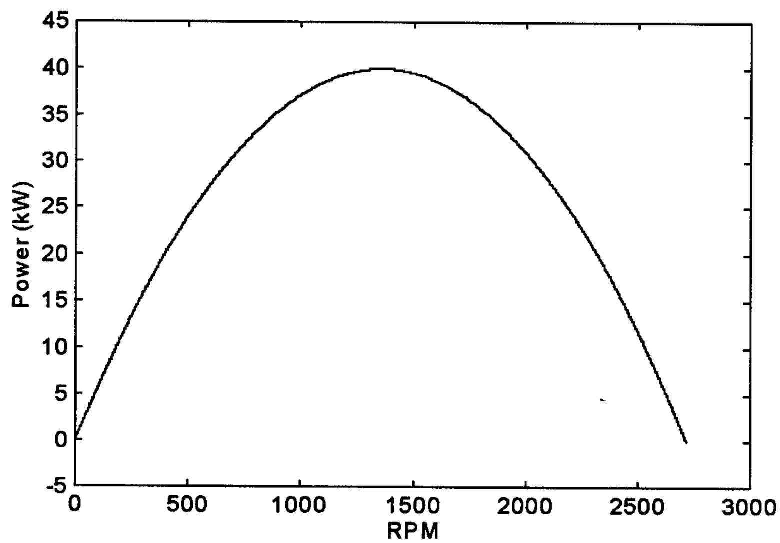

Figure 18: Power Versus RPM for Simulated Expander.

The next major difference involves vehicle throttling and massflow calculations. In order to allow a simple approximation of the more advanced motors, the simulation only allows two settings, full power or no power. If the vehicle is below the desired speed, it goes to full power, if above the desired speed, it coasts. There is an added feature which allows for braking if the vehicle is too much faster than the desired speed (more than 3 m/s). This allows a first approximation of the vehicle performance without needing to model a throttling technique and pressure response for the future motor.

ddrivea.m shifts gears by calculating which gear will deliver the most torque to the wheels at a given vehicle speed. This gear is selected and the motor's RPM is used to determine maximum power and torque available to the wheels. The vehicle's acceleration is then calculated from the wheel torque, drag, mass, and road angle, as before. The massflow for each timestep is calculated using the power and the specific work calculated for the motor.

Using reasonable assumptions about the LN2000 systems, the performance of the ideal follow-on motors was predicted. The adiabatic motor was calculated to have a specific work of 141.4 kJ/kg LN_2. This was found from in input pressure of 150 psi, output pressure of 16 psi, and input temperature of 288 K. This assumes no losses during the expansion process. The isothermal motor is even better, predicting 191.3 kJ/kg LN_2 at a constant temperature of 288 K. Pump work is neglected. The predicted performance of the LN2000 vehicle is summarized in Table 4. An improved motor will provide for more rigorous testing of the liquid nitrogen heat exchange system.

As stated earlier, cryogenic automobiles will not be commercially viable until they can match the performance of gasoline powered vehicles. In order to predict the performance of a car designed to perform like a consumer vehicle, another Matlab routine was constructed. *ddrivef.m*, found in Appendix C, predicts the performance of a reasonably streamlined, extremely lightweight vehicle with a high pressure plumbing system. Specifically, the vehicle is assumed to be 1030 kg to start out, including the mass of the fuel. The car is assumed to carry 400 L of liquid nitrogen and have a maximum pressure of 960 psi. The vehicle expands the gas through a turbine system with three reheats to 288 K and a polytropic efficiency of 0.95. Using these assumptions, a specific work of 290 kJ/kg is calculated for the vehicle. The motor is set to put out 30 kW at 1358 RPM, similar to the one shown in Figure 18. As in the predictions above, part-power efficiency is assumed to be the same as design point. It is useful to keep in mind that this could not be achieved in real applications. The simulated car is aerodynamically comparable to modern sedans with a drag coefficient of 0.4 and a frontal area of 1.88 m^2.[32] The

anticipated performance of the purpose-built car is also summarized in Table 4. Note that the car is predicted to achieve about 120 miles range in city driving, and would perform better on the highway. It could also be refueled in less than 30 minutes.

Table 4: Predicted Performance of Future Configurations.

	LN2000 - Adiabatic	LN2000 - Isothermal	Purpose Built
Max. Range	7.5 km	10.1 km	192 km
0-30 mph	5 s	5 s	5 s
Max. Speed	64.7 mph	64.7 mph	79.5 mph
Hill-Climb at 20 mph	24% grade	24% grade	25% grade

The excellent hill-climb abilities of these vehicles are due to the high torque at low RPM characteristics of air motors. An actual motor would probably have less of an ability to accelerate and climb due to internal losses.

V. Actual Vehicle Performance

The LN2000 vehicle has undergone various tests to measure it's road performance and potential. Its operational performance was also observed. The vehicle, despite its limitations, performed exceptionally well. There were difficulties because it's a conglomerate of non-optimized parts; these difficulties are discussed within. The tests validated predictions of heat exchanger performance, including resistance to frost build-up. The rapid construction and sustained operation of LN2000 is another measure of the car's performance. The vehicle concept is demonstrated by LN2000's existence and continued operation.

DATA ACQUISITION METHODS

In order to obtain quantifiable performance data, a variety of observations were made during each vehicle test run. The instrumentation available included four pressure gauges, a liquid level gauge, a tachometer, an odometer, and a speedometer. Data collection was done by manual observation of the gauge readings and recording of those observations into the laboratory notebook. Often this was done by an observer sitting in the passenger seat of LN2000 while it was in motion. The observations made varied with each test run and the objective of the run. Various environmental conditions were often included with the performance data as well. While the data acquisition methods were not highly precise, much valuable information was still obtained. Even more information about individual components could be gathered using electronic pressure transducers installed in the plumbing as described in Chapter VI.

A second hindrance to the quality of the data is the fact that the vehicle was operated in hilly public streets, not a closed test course. All of the vehicle test runs were made after fueling at the University of Washington Department of Aeronautics and Astronautics machine shop. The streets were often clogged with vehicles and pedestrians going to and from classes. The available streets for tests were hilly and contained stop signs

approximately every half mile. The speed limit on the University of Washington campus is 20 mph. Data like maximum speeds, accelerations, and ranges were difficult to reliably obtain because of the stop signs, speed limits, pedestrians, bicycles, and car traffic.

ACTUAL ROAD PERFORMANCE

A variety of road performance characteristics were found for the LN2000 vehicle. Because of the test conditions described above, only a limited comparison can be made with the predicted performance described in Chapter IV. The vehicle's maximum range on a full tank of liquid nitrogen was measured as 3.3 km (2.1 mi). The course for this measurement is a very rough approximation for the Federal Urban Driving Cycle. The car was subjected to periods of full torque (climbing hills) interspersed with periods of coasting and braking. The LN2000 vehicle traveled approximately 0.9 miles uphill, then made laps in a parking lot which had a small slope to it until the fuel was nearly depleted. The car was then driven back down the hill, coasting much of the way, to the garage. The measurements were made using the LN2000 odometer and verified over the same route using the odometer on another automobile. The ambient temperature for this run was 44°F. The atmospheric pressure was 30 in Hg, and the relative humidity was 75%. After the 20 minute run, during which the fans were constantly running, the heat exchanger had frost built-up on all the fins of all the tubes. After leaving the fans running for a few minutes, the frost dissipated

LN2000's maximum measured speed was 22 mph. This is not necessarily the maximum potential speed for the vehicle, however. This measurement was difficult due to two major factors. The longest stretch between stop signs was about a half mile, and the longest flat stretch of street available for testing was one tenth of a mile. The car's speedometer was used to obtain this data. During this test, the ambient temperature was 46°F, barometer was 30.3 in Hg, and there was a light rain falling. The fans were running

the entire time and no frost was seen on the heat exchanger fins. Total driving time was approximately ten minutes.

The best observations of vehicle acceleration were taken during the maximum speed tests. The tests were skewed by the slight downward slope of the road, but the vehicle accelerated to 21 mph in approximately 30s.

LN2000 was able to climb over 7.6 cm high curbs and steep inclines at slow speeds. The steepest hill LN2000 was observed to climb has a 9.54% grade. The vehicle was unable to accelerate to 20 mph on an uphill grade. The maximum speed reached on an uphill was 14 mph, on a 2.5% grade. All of the above information is summarized in Table 5.

Table 5: Actual LN2000 Road Performance.

	LN2000 Road Tests	Predicted Performance	% Difference
Max. Range	3.30 km	3.73 km	-12%
0-30 mph	*	23 s	*
Max. Speed	22.0 mph	38.6 mph	-43%
Hill-Climb	**	5.2% grade	**

* maximum speed reached is 22 mph

** Maximum uphill speed reached is 14 mph

The discrepancy between Kubvan performance and the specific energy numbers presented in Chapter II is largely due to the air motor. The motor forces a reduction in maximum operating pressure from ~350 psi to 125 psi. About 27% of the total available work in the gas is thrown away during this throttling process. The motor also has a high percentage of dead volume (in the manifold) and does not reach atmospheric exhaust pressures, because it operates more like a hydraulic motor than like an expander. The motor volume expansion ratio is estimated at about 2.9, based on the dimensions of the motor. That leaves an exhaust pressure of about 30 psig, which further reduces the work done by the gas. Generally, nitrogen consumption can be reduced by increasing the motor pressure ratio.[34] A large amount of gas is completely lost into the crankcase and simply

vents to the atmosphere. This is most likely due to a poor of seal around the pistons, normally provided by the oil. The lost potential work and low expander efficiency translate into a specific work of only 31 kJ/kg-LN_2, compared with the 200-320 kJ/kg-LN_2 used in Figure 5. The loss in performance for the current expander can easily be seen in Figure 19. Both range and acceleration would increase with improved expander efficiency. The performance benefit of increasing operating pressure is also clearly seen. The current motor tests the heat exchanger by consuming far more liquid than would be necessary with a more efficient expander. Continually running at full throttle and low speeds is a worst-case scenario for the nitrogen vaporization system.

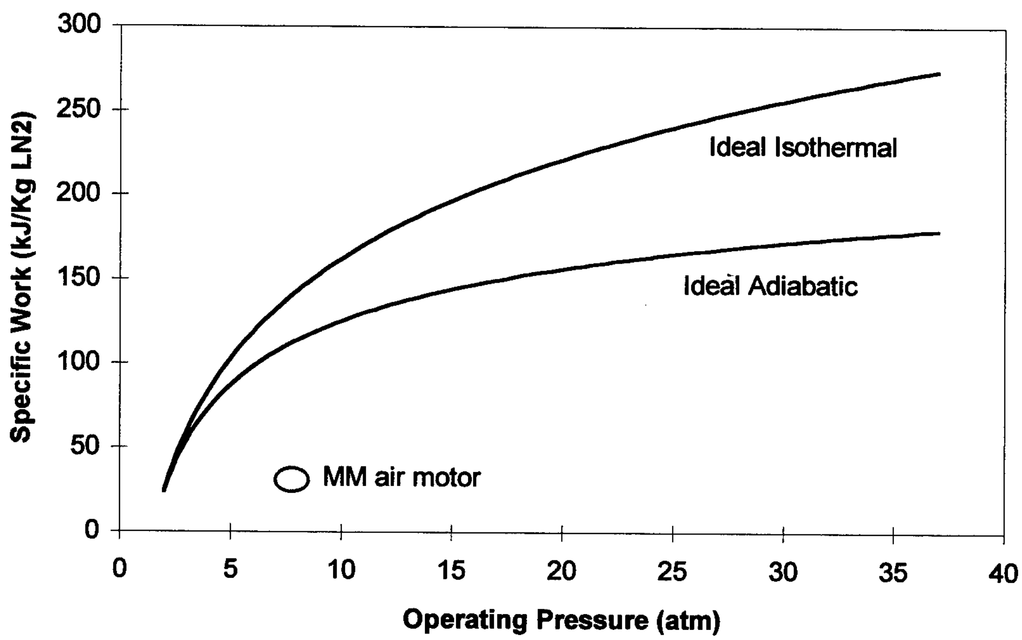

Figure 19: Expander Specific Work Versus Pressure.[14]

OTHER PERFORMANCE ISSUES

A range of equally important performance issues were investigated using the LN2000 concept demonstrator. Much was learned about the robustness of the concept and components as it was operated for an extended period under a variety of conditions. Issues pertaining to cost and simplicity of operations were explored, including potential hurdles to customer acceptance of the concept. The overall performance of the plumbing and pressurization system and the air motor provided useful information for future work. Lastly, the refueling process was demonstrated and much was learned.

The LN2000 served as an excellent testbed for the robustness of various components and systems unique to cryogenic automobile propulsion. The car was operated under a variety of conditions, for a period of about 5 months. It performed runs in all weather conditions, however, ice and snow have not yet been investigated. Significantly, the vehicle did not perform noticeably better on warm days than on cold ones. The vehicle was driven on city streets and even over curbs on several occasions (though not fast), with no adverse effects. No components had to be replaced due to failure during the testing process. The vehicle required only minimal maintenance, including refueling the pressurization bottles and the dewar, and recharging the batteries. The heat exchanger, in particular, was found to be robust and sturdy.

Some of the motor's poor performance was attributed to a lack of sealing and lubrication of the pistons. This contributed to loss in pressure through the blowby. The temperature of the nitrogen entering the motor was significantly lower than ambient as indicated by the temperature of the blowby gas. The oil used in the motor, while it was recommended by the motor manufacturer, was not suited for use at these temperatures. Changing the oil to a lighter weight might allow the motor to perform better.

An interesting phenomenon occurred due to the temperature of the vehicle plumbing. During extended, high power runs, the heat exchanger fins tended to frost. This build-up never exceeded a thin coating on the fins, but indicates a possible problem for a longer

range vehicle running at higher continuous massflow rates. The plumbing upstream of the heat exchanger tended to build up a layer of frost on all runs. While this was not particularly inconvenient for an experimental vehicle, it does need to be addressed in the design of a commercial vehicle, as much of the vehicle's interior became damp when the frost melted. Those pieces of plumbing which were covered with 1/2 in (1.3 cm) thick plastic insulation barely frosted at all, while the unprotected inlet manifold to the heat exchanger developed frost up to 1/4 in thick. The economizer tubes remained covered with frost for over 30 minutes after a long run, due to their large thermal mass. The vehicle exhaust hose also froze. The temperature of the exhaust caused a visible cloud to form during high massflow runs, especially when the dew point of the air was close to the ambient temperature.

Overall, the car was simple to operate for a prototype vehicle. It was driven with only one operator at a time. The car generally handled like any other automobile, with a few notable exceptions. The throttle's position near the driver's right hand and manual transmission made shifting awkward. A foot operated throttle would be extremely desirable for future modification. The vehicle was tolerant of user mistakes such as overpressurization, refill procedure errors, and rough driving. LN2000 was so simple to maintain, only a couple of crescent wrenches and a trickle-charger (for the batteries) were necessary.

Another important advantage of cryogenic vehicles is the potential for relatively quick refuel when compared to electric cars. Over the course of 5 months, the car was refueled approximately 20 times. The average time to fill the dewar was about 25 minutes. This did not include moving equipment around or letting the hose warm up before disconnecting. All put together, a refuel took about 65 minutes. The process was certainly more complicated than it would be for a production vehicle, and involved opening and closing various valves and checking the pressure in the two LN_2 dewars. Care had to be taken to not hurry the fill procedure or rush through the pre-run setups. One difficulty encountered was a problem with determining when the tank was full. The

manufacturer suggested that the tank be weighed to determine when it was full, but that was impractical for this application.[29] It was decided that when liquid dripped from the vent tube, the tank was full and so filling stopped. Sometimes this proved inaccurate, though. The dewar tended to leak after refueling for about two hours, only maintaining a pressure of 150 psi. After the top of the tank - near the liquid level gauge and valves - warmed up, the dewar maintained pressure up to 350 psi. The valve connecting the dewar gas vent to the outside also needed to warm up for a few minutes before it would seal.

The heat exchanger performed noticeably better with the fans on than without. The best available indicator of heat exchanger performance was amount of frosting and there was a definite increase in frost accumulation when the fans were not in operation. This is also due to the heat exchanger's location at the rear of the vehicle and LN2000's low speeds. Considerably more airflow went through the exchanger when the fans were in operation. There were indications that either the heat exchanger or economizer was causing significant pressure drop at high massflows. During maximum RPM tests, the pressure in the dewar was about 345 psi while the driver's regulator read only about 150 psi, on both sides of the regulator. That pressure drop decreased the available pressure to the throttle and so probably contributed to the lower than anticipated maximum RPM.

VI. Recommendations

A significant amount of practical information has been gathered during the design, construction, and testing of LN2000. Much more will be required before a prototype cryogenic automobile can be produced. Several improvements would allow LN2000 to better test the nitrogen vaporization system. Instrumentation, particularly pressure and temperature sensors, would be the most valuable addition to the vehicle. This would allow much more detailed characterization of heat exchanger performance. Another addition would be to install a system to charge the batteries and provide power for onboard electrical systems. This could be done with either an alternator or solid-state thermoelectric generators. The thermoelectrics would serve the dual purpose of adding heat to the nitrogen and providing electric power. In fact, this approach is planned for a vehicle using a hybrid electric-nitrogen propulsion system.[2]

The most important improvement for the LN2000 vehicle would be to replace the current motor with a more efficient expander. There is much to be learned from designing a quasi-isothermal expander and testing it using the current vehicle set-up. A purpose-built motor would provide a more realistic test for the heat exchanger design. The preliminary design and anticipated performance of this type of expander is addressed elsewhere.[27] Further additions to the LN2000 vehicle might include installing a cryogenic pump or a second liquid nitrogen dewar.

The next step beyond LN2000 would be the construction or modification of a purpose-built cryogenic vehicle. This vehicle would be lighter weight, have better aerodynamics, a larger fuel tank, and a higher operating pressure. A cryogenic vehicle designed from the ground up would take advantage of the knowledge acquired from LN2000. An automatic transmission tailored to the performance of the expander (as opposed to the performance of a normal gasoline engine) would be a large improvement. The opportunity to place the heat exchanger in a more advantageous position could substantially improve its performance. Future system design will also need to account for

the thermal performance of the vaporization system. The one designed for LN2000 has optimum performance at cruise conditions, but doesn't perform as well under sustained high massflow conditions. This would indicate an advantage of a hybrid-electric drive system. Or, under severe conditions, a combination active and passive frost prevention system might be indicated. This system would use active frost removal only when absolutely needed.[28]

Further work on cryogenic automobile propulsion should include the investigation of a wide range of issues. As mentioned in Chapter II, there are a wide variety of options for capitalizing on the thermodynamic potential of a cryogenic energy storage device. These options should be evaluated on their merits, not merely for expedience. A more thorough investigation of safety issues, especially crash safety and the performance of the high pressure plumbing must be conducted. An economic and technical analysis of existing LN_2 infrastructure and future needs would be an excellent asset. Also important to the future of cryogenic automobiles is a detailed investigation of the fuel handling needs of these vehicles. This could include everything from the availability and performance of cryogenic pumps to refueling mechanisms. Refueling issues to be explored include necessary safety features for fuel tanks on commercial automobiles and adapting infrastructure at existing gasoline retailers. An effort to improve the efficiency of air liquefaction plants and cryogenic transportation infrastructure would aid in the economic outlook for this type of vehicle as well.

VII. Conclusions

The cryogenic automobile can compete in the alternative vehicle market. The concept has proven to be a straightforward way to power a car without tailpipe emissions. This paper describes the construction, modeling, and testing of a liquid nitrogen powered automobile. The vehicle was used to test the performance of an new frost-resistant nitrogen vaporizer system. The heat exchanger performed well, resisting the build-up of frost and allowing the vehicle to run in a variety of conditions. No major technical hurdles were discovered which might hinder the development of this class of zero-emission vehicle, however work must be done to bring this concept to an acceptable level of performance. The potential widespread environmental benefits of this type of automobile give added incentive to further develop cryogenic propulsion. There is a growing world demand for this class of vehicle. Additionally, cryogenic automobiles could potentially compete with combustion vehicles for range and economic performance.

Besides serving as a test vehicle, LN2000 demonstrated the viability of the cryogenic automobile propulsion concept. The actual street performance of the vehicle closely matched the performance predictions made with computer modeling. The LN2000 vehicle is remarkably reliable and robust for a test platform. The car was simple to operate after a few minutes of training and practice.

This paper demonstrated that a relatively simple method may be used to predict the road performance of future cryogenically powered automobiles. The method is reasonably accurate and offers insight valuable in the system design process. This analytical prediction can also help in vehicle design for specific tasks or markets.

A base of experience working with a cryogenic test vehicle has been established which will be valuable in further investigations of the concept. This experience covers design, fabrication, modification, and operation of a liquid nitrogen powered automobile system. The process has many parallels in the mature field of combustion powered automobile design and production. Cryogenic powered automobiles can be made to

perform and operate very much like existing cars and trucks. Maintenance and infrastructure represent possible challenges to the commercial implementation of this type, however there is much cross-over with existing industries.

The cryogenic powered automobile has the potential to change the world's roads, but more work must be done before even one will be on the highway.

End Notes

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Appendix A: Vehicle Performance Simulation Code

DDRIVE.M

```
% This is the main routine for the driving cycle simulations,
% Using the capability to throttle the input to the mm motor to differing pressures
% taking inputs for the desired velocity from the city driving cycle
% Run loadnist.m before running this program in order to load the nist data

global n2_101 n2_200 n2_300 n2_400 n2_500 n2_600 n2_700 n2_800;
global n2_900 n2_1000 n2_1100 n2_1200 n2_1300 n2_1400 n2_1500;
global n2_1600 n2_1700 n2_1800 n2_1900 n2_2000 n2_2100 n2_2200;
global n2_2300 n2_2400 n2_2500 n2_2600 n2_2700 n2_2800 n2_2900;
global n2_3000 n2_3100 n2_3200 n2_3300 n2_3400 n2_3500 n2_3600;
global pVdot;

clear;

%       List of Variables
% Rpm(i) = calculated rpm of the mm motor - due to the velocity
% v(i) = calculated velocity of the car  (m/s)
% vstart  = starting velocity of the car (m/s)
% Tout(i) - torque put out by the motor (Nm)
% Pout(i) - power put out by the motor (kW)
% a(i) - acceleration of the car (m/s^2)
% step = step size in seconds (s)
% m_o = starting mass of the car, from paramsd (kg)
% time(i) = gives a time reference for graphs (s)
% gear = converts velocity into rpm - changes gears based on velocity
% PwrA(i) = acceleration based on the power available (m/s^2)
% TrqA(i) = acceleration based on the torque available (m/s^2)
% differential = gear ratio of the differential gear
% diam = diameter of tire (m)
% mdot(Rpm) = a function of rpm which gives massflow of LN2 in (kg/s)
% massflow  = instantaneous mass flow  (kg/s)
```

```
% r = rolling friction coefficient from paramsd
% theta = angle in radians of the road (rad)
% slope70 =

% Load the operating parameters
paramsd;
trani3;
vdotd;
p_perf2;

% Set the step size in seconds (s)
step = 1;                          % s

% Set the starting conditions
t(1) = time(1);
Rpm(1) = 0;
Tout(1) = 0;
a(1) = 0;
drag(1) = 0;
friction(1) = 0;
psiT(1) = 0;
tgtA(1) = 0;
massflow(1) = 0;
%
% speed(1) = 17.94;                % 40 mph
% speed(1) = 23.5669;              % max speed (w diff = 2:1) = 52.7 mph?????
%
v(1) = speed(1);
gear(1) = 0;
totalmdot = 0;
theta = 0;
i = 1;

differential = 3.67/2;
```

```
diam = 0.6;                             % m   Wheel diameter - measured

while totalmdot <= N2                   % Range on Tanks
% while v(i) < 8.9408                   % 20 mph - for hill climb
% while v(i) < 13.41                    % 30 mph
% while v(i) < 17.94                    % 40 mph
% while i < 1372                        % Whole City Cycle
% while i < 765                         % Whole Highway Cycle

    i = i + 1;                          % goes to next time step
    t(i) = time(i);                     % s
%
    mass = m_o-totalmdot;               % kg   Decreases mass of car as fuel is consumed
%   mass = m_o;
%


%
% speed(i) = 17.94;                     % 40 mph        Setting desired speed to accelerate to
% speed(i) = 13.41;                     % 30 mph
% speed (i) = 8.9408;                   % 20 mph
% speed(i) = 23.25;                     % 52 mph
% speed(i) = 40;                        % max out!
%   if speed(i) > 13.41
%       speed(i) = 13.41;               % Limits max speed to 30 mph
%   end;
%

    % Now calculate current velocity using the acceleration calculated in the last step,
    % or the last speed desired, for braking:
    if tgtA(i-1) > 0
        v(i) = v(i-1) + a(i-1)*(t(i)-t(i-1));   % m/s
    else
        v(i) = speed(i-1);
    end;
```

```
% What's my new target acceleration? (m/s^2) : [speed wanted - current speed] / delta time
tgtA(i) = (speed(i) - v(i)) / (t(i) - t(i-1));                    % m/s^2

% Calculate drag and rolling friction forces based on velocity and vehicle weight
   % Calculate the aerodynamic drag (N)
   drag(i) = 0.5*rho*Cd*area*v(i)^2;

   % Calculate the rolling resistance (N)
if v(i) < 0.1
   friction(i) = 0;
else
   friction(i) = r*(mass)*cos(theta)*g*(1 + 1e-3*v(i) + 1e-5*v(i)^2);
end;

%%%%%%%%%%%%%%%%%% Find Rpm %%%%%%%%%%%%%%%%%%%%%%
   % What gear should I be in, based on last velocity and my transmission -
   % using gears from trani3, shifting using torque/velocity curves for different gears
   %          %1:1 gear ratio in motor coupling
   %                 % 2:1 gear ratio in motor coupling

   if v(i) <= 6 %3.5   % 6
      gear(i) = firstgear;
   end;
   if v(i) > 6 %3.5    % 6
      gear(i) = secondgear;
   end;
   if v(i) > 10 %5.5   % 10
      gear(i) = thirdgear;
   end;
   if v(i) > 14 %7.5   % 14
      gear(i) = fourthgear;
   end;
   if v(i) > 20 %10.5  % 20
```

```
    gear(i) = fifthgear;
end;
    % What's my rpm? based on that velocity and the gear I'm in?
% Rpm = Velocity / circumference of tires * gear * differential
Rpm(i) = (v(i)/(pi*diam))*60*gear(i)*differential;


% What amount of torque is required to get the target acceleration?
% Torque = ( (mass*accel) + drag + friction + weight*sin(theta) ) )*(wheel radius)/(gear ratios *.85)
% 0.85 for torque transmission inefficiencies
Treq(i) = ((tgtA(i)*(mass)) + drag(i) + friction(i) + mass*g*sin(theta)) * (diam/2)/
            (gear(i)*differential*.85);
% "Coasting" feature.
if Treq(i) < 0                                          % Nm
    Treq(i) = 0;                               % Nm
end;


% What pressure would be required to get that torque?
%%%%%%%%%%%%%%%%%%%%%%%%%% Torque Section %%%%%%%%%%%%%%%%%%%%%%


% What are the three "torque points" at that rpm (for 90, 80, 70 psi)
Tout90 = polyval(p_T90, Rpm(i));               % Nm
Tout80 = polyval(p_T80, Rpm(i));               % Nm
Tout70 = polyval(p_T70, Rpm(i));               % Nm


% curve fit a pressure vs torque curve for this rpm
P = [0 70 80 90];                              % psi
tPoints = [0 Tout70 Tout80 Tout90 ];                    % Nm
[Tcurve,S] = polyfit(tPoints,P,3);


% find out the pressure required to put out the required torque
slope70 = polyval(polyder(Tcurve),Tout70);


if Treq(i) < Tout70
    psiT(i) = (Tout70-Treq(i))*(-slope70)+70;  % psi
else
```

```
    psiT(i) = polyval(Tcurve,Treq(i));  % psi
  end;


  if psiT(i) > 90                          % The most pressure available to motor is 90 psi
    psiT(i) = 90;                          % psi
    Tout(i) = polyval(p_T90, Rpm(i));      % Nm
  else
    Tout(i) = Treq(i);                     % Nm
  end;

  if Treq(i) < 0.1      % Shuts off massflow if no torque is required of the motor
    psiT(i) = 0;
  end;

%%%%%%%%%%%%%%%%%% Acceleration Calc %%%%%%%%%%%%%%%%%%

  % What's my acceleration based on the torque output? (m/s^2)
  % Use T/(radius of tire) = Favailable   => measured diameter of car at .6 m
  % Also using a factor of 0.85 for inefficiencies in torque transmission
  % Circumference of gear depends on which gear you're in - again using trani3:

  TrqA(i) = ( (Tout(i)*.85*gear(i)*differential/(diam/2)) - drag(i) - friction(i) - mass*g*sin(theta)) /
              (mass);

  % What's my acceleration?
    a(i) = TrqA(i);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%POWER%%%%%%%%%%%%%%
  Pwr(i) = 2* pi * Tout(i) * Rpm(i) / 60000;                 % (kW)


%%%%%%%%%%%%%%%%%%%% MDOT CALC %%%%%%%%%%%%%%%%%%%%%%%%%%
  % What's my mdot at that Rpm?  (kg/s)
  % Assumptions: volumetric flow data is taken from table faxed to us: 348 cfm at max HP
```

```
    % (~1070 rpm).  Then, find mdot using 70 F and 1 atm for cfm, then, get input vdot at 90 psi, 1070
    % rpm.
    %  Assuming it's linear from zero rpm, and assuming gas temperature is constant at 288 K

    massflow(i) = mdotd(Rpm(i),(psiT(i)*6894.757));          % (kg/s)

    % Calculate the total LN2 consumed so far
    totalmdot = trapz(t,massflow);                           % (kg)

%   if i > 45                               % feature stops car after 45 seconds (hill-climb)
%       v(i) = 20;
    if i > 1372                             % feature stops car at end of City Cycle
        totalmdot = 20000;
    end;

end;

totalmdot                         % (kg)
Totaltime = max(t)                % (s)
Totalrange = trapz(t,v)/1000      % (km)

figure(1);
clg;
plot(t,v*2.23,time,speed*2.23);
grid;
xlabel('time (s)');
ylabel('mph');
title('Velocity versus Time');
legend('Car Speed','Cycle Target');
```

PARAMSD.M

```
% This is the parameter file for the driving cyle simulations.
```

```
precis = 0.001;

% Load the driving cycle
load ctyspeed;                      % Speed (mph)
speed = speed/2.237;                % Speed (m/s)
load ctytime;                       % Time (s)

% Automobile parameters
P = (90) * 101320/14.7;             % Operating pressure (Pa)
m_o = 1430;                         % Starting mass (kg)
area = 2.4;                         % Frontal area (m^2)
Cd = 0.8;                           % Coefficient of drag
r = 0.013;                          % Rolling resistance
n = 1;                              % Number of LN2 Dewars in vehicle
N2 = n*(0.075)*nist(2413165,119,'Density');     % Stored nitrogen (kg)   (number of tanks)*(tank
    volume m^3)*density of sat liq Nit at 350 psi

% Other parameters
rho = 1.226;                        % Density of air (kg/m^3)
g = 9.81;                           % Gravity (m/s^2)
```

TRANI3.M

```
% This is an m-file that will explore the gear ratios in a volkwagon
% five-speed transmission - based on using a series MM air motor

firstgear = 3.45;
secondgear = 1.94;
thirdgear = 1.37;
fourthgear = 1.03;
fifthgear = 0.75;
```

VDOTD.M

```
% This is an m-file function that calculates the mass flow to the
% MM series air motor given an rpm and pressure.

global pVdot;
% This is a little program to find the reference vdot versus rpm linear fit for the
% mm series motor given the faxed data point - 348 cfm at max HP - assumed to mean
% scfm which is at 70 F and 1 atm. The pVdot fit then allows the mdotd function to
% find the massflow through the motor at a certain rpm and pressure. (code for mdotd
% included)

RefRhoOut = nist(101325,294.3,'Density');      % (kg/m^3) Density at 70 F and 1 atm for SCFM
mdotin = (348/(35.315*60))*RefRhoOut;          % (kg/s) Mdot reference (348 SCFM converted to m^3/s)*density
RefRhoIn = nist(620528,288,'Density');         % (kg/m^3) Density at 90psi, 288 K
vdotin = mdotin/RefRhoIn;                      % (m^3/s) vdot reference - 1070 rpm

pVdot = [vdotin/1070 0];                       % (m^3/s)
```

CHECK2.M

```
% This is a check to see if the torque versus pressure versus rpm curves generated for ddrive make sense
clear;

% Calculate the torque curve fit at 90 psi
T90 = [138 103.5 69 34.5 0]*(.3048*4.448);     % Torque (Nm)
RPM_T90 = [0 624 1159 1645 2140];
[p_T90,S] = polyfit(RPM_T90,T90,1);

% Calculate the torque curve fit at 80 psi
T80 = [121 103.5 69 34.5 0]*(.3048*4.448);     % Torque (Nm)
RPM_T80 = [0 490 1070 1605 2110];
[p_T80,S] = polyfit(RPM_T80,T80,1);
```

```
% Calculate the torque curve fit at 70 psi
T70 = [92 69 46 34.5 0]*(.3048*4.448);          % Torque (Nm)
RPM_T70 = [0 624 1070 1293 1917];
[p_T70,S] = polyfit(RPM_T70,T70,1);

% Calculate the torque curve fit at 125 psi - based on data points obtained using check2 program
% check2 program used a 3rd order polynomial fit to find pressure given torque.  I graphically used
% this plot to go from 125 psi to the torque points at differing RPM
T125 = [170 160 127 87 44 21]*(.3048*4.448);     % Torque (Nm)
RPM_T125 = [0 105 535 1070 1605 1900];
[p_T125,S] = polyfit(RPM_T125,T125,1);

% Calculate the power curve fit at 90 psi
HP90 = [0 3.8 7.6 11.4 15.2 11.4 7.6 3.8 0];% Power (HP)
RPM_HP90 = [0 150 300 500 1070 1605 1800 2000 2140];
[pHP90,S] = polyfit(RPM_HP90,HP90,2);

% Calculate the power curve fit at 80 psi
HP80 = [0 3.8 7.6 11.4 13.6 11.4 7.6 3.8 0];% Power (HP)
RPM_HP80 = [0 155 356 680 1050 1470 1783 1970 2090];
[pHP80,S] = polyfit(RPM_HP80,HP80,2);

% Calculate the power curve fit at 70 psi
HP70 = [0 3.8 7.6 9.8 7.6 3.8 0];    % Power (HP)
RPM_HP70 = [0 195 540 910 1428 1763 1932];
[pHP70,S] = polyfit(RPM_HP70,HP70,2);


% For now, what's my Rpm?
BOB = 1070;

%%%%%%%%%%%%%%%%%%%%%%%%% Torque Section %%%%%%%%%%%%%%%%%%%%
```

```
        % What are the three "torque points" at that rpm (for 90, 80, 70 psi)
        Tout90 = polyval(p_T90, BOB);
        Tout80 = polyval(p_T80, BOB);
        Tout70 = polyval(p_T70, BOB);
        Tout125 = polyval(p_T125, BOB);

        % curve fit a torque vs pressure curve for this rpm
        % pressure = [0:1:125];
        P = [0 70 80 90];
        tPoints = [0 Tout70 Tout80 Tout90 ];   % FtLb
        [Tcurve,S] = polyfit(tPoints,P,3);

        % find out the torque produced by the motor at each input pressure
        slope = polyval(polyder(Tcurve),Tout70);
for i = 1:Tout70
        tor(i) = i;
        pres(i) = (Tout70-i)*(-slope)+70;
        thrd(i) = polyval(Tcurve,tor(i));
end;
for j = Tout70:(Tout125+(Tout125*.1))
        tor(j) = j;
        pres(j) = polyval(Tcurve,tor(j));
        thrd(j) = polyval(Tcurve,tor(j));
end;

figure(1);
clg;
plot(tor,thrd,'g',tor,pres,'w',Tout70,70,'wo',Tout80,80,'wo',Tout90,90,'wo',Tout125,125,'wo');
% grid;
legend('3rd Order Fit ','Curvefit','Data');
% title('Pressure vs. Torque for 1070 RPM');
ylabel('Pressure (psi)');
xlabel('Torque (Nm)');
```

P_PERF2.M

```
% This code figures out what the power and torque versus Rpm curves are for three different pressures
% The data is taken from the MM motor sheet faxed to us.

rpm = [0:10:2140];

% Calculate the power curve fit at 90 psi
HP90 = [0 3.8 7.6 11.4 15.2 11.4 7.6 3.8 0]*(745.7); % Power (W)
RPM_HP90 = [0 150 300 500 1070 1605 1800 2000 2140];
[pHP90,S] = polyfit(RPM_HP90,HP90,2);

% Calculate the power curve fit at 80 psi
HP80 = [0 3.8 7.6 11.4 13.6 11.4 7.6 3.8 0]*(745.7); % Power (W)
RPM_HP80 = [0 155 356 680 1050 1470 1783 1970 2090];
[pHP80,S] = polyfit(RPM_HP80,HP80,2);

% Calculate the power curve fit at 70 psi
HP70 = [0 3.8 7.6 9.8 7.6 3.8 0]*(745.7);          % Power (W)
RPM_HP70 = [0 195 540 910 1428 1763 1932];
[pHP70,S] = polyfit(RPM_HP70,HP70,2);

% Calculate the torque curve fit at 90 psi
T90 = [138 103.5 69 34.5 0]*(.3048*4.448);          % Torque (Nm)
RPM_T90 = [0 624 1159 1645 2140];
[p_T90,S] = polyfit(RPM_T90,T90,1);

% Calculate the torque curve fit at 80 psi
T80 = [121 103.5 69 34.5 0]*(.3048*4.448);          % Torque (Nm)
RPM_T80 = [0 490 1070 1605 2110];
[p_T80,S] = polyfit(RPM_T80,T80,1);

% Calculate the torque curve fit at 70 psi
```

```
T70 = [92 69 46 34.5 0]*(.3048*4.448);          % Torque (Nm)
RPM_T70 = [0 624 1070 1293 1917];
[p_T70,S] = polyfit(RPM_T70,T70,1);

% Calculate the torque curve fit at 125 psi - based on data points obtained using check1 program
% check1 program used a 3rd order polynomial fit to find pressure given torque.  I graphically used
% this plot to go from 125 psi to the torque points at differing RPM
T125 = [170 160 127 87 44 21]*(.3048*4.448);    % Torque (Nm)
RPM_T125 = [0 105 535 1070 1605 1900];
[p_T125,S] = polyfit(RPM_T125,T125,1);
```

MDOTD.M

```
% This is an m-file function that calculates the mass flow to the
% MM series air motor given an rpm and pressure.

function [massflow] = mdotd(rpm,pressure)

global n2_101 n2_200 n2_300 n2_400 n2_500 n2_600 n2_700 n2_800;
global n2_900 n2_1000 n2_1100 n2_1200 n2_1300 n2_1400 n2_1500;
global n2_1600 n2_1700 n2_1800 n2_1900 n2_2000 n2_2100 n2_2200;
global n2_2300 n2_2400 n2_2500 n2_2600 n2_2700 n2_2800 n2_2900;
global n2_3000 n2_3100 n2_3200 n2_3300 n2_3400 n2_3500 n2_3600;
global pVdot;
Vdot = polyval(pVdot,rpm);                          % (m^3/s)
% What's the density of the gas flowing into the engine, based on 288 K temp
% and given pressure, psiT?  This uses nist.m from pete\carsims\utility to find rho.
if pressure > 0.101e6
    gasrho = nist(pressure,288,'Density');          % kg/m^3
    massflow = Vdot*gasrho;                         % Mdot (kg/s)
else
    massflow = 0;
end;
```

Appendix B: Advanced Motor Simulation Code

DDRIVEA.M

```
% This is the main routine for the driving cycle simulations,
% Using the capability to throttle the input to the mm motor to differing pressures
% taking inputs for the desired velocity from the city driving cycle
% Run loadnist.m before running this program in order to load the nist data

global n2_101 n2_200 n2_300 n2_400 n2_500 n2_600 n2_700 n2_800;
global n2_900 n2_1000 n2_1100 n2_1200 n2_1300 n2_1400 n2_1500;
global n2_1600 n2_1700 n2_1800 n2_1900 n2_2000 n2_2100 n2_2200;
global n2_2300 n2_2400 n2_2500 n2_2600 n2_2700 n2_2800 n2_2900;
global n2_3000 n2_3100 n2_3200 n2_3300 n2_3400 n2_3500 n2_3600;
global pVdot;

clear;

%       List of Variables
% Rpm(i) = calculated rpm of the mm motor - due to the velocity
% v(i) = calculated velocity of the car  (m/s)
% vstart  = starting velocity of the car (m/s)
% Tout(i) - torque put out by the motor (Nm)
% Pout(i) - power put out by the motor (kW)
% a(i) - acceleration of the car (m/s^2)
% step = step size in seconds (s)
% m_o = starting mass of the car, from paramsd (kg)
% time(i) = gives a time reference for graphs (s)
% gear = converts velocity into rpm - changes gears based on velocity
% PwrA(i) = acceleration based on the power available (m/s^2)
% TrqA(i) = acceleration based on the torque available (m/s^2)
% differential = gear ratio of the differential gear
% diam = diameter of tire (m)
% mdot(Rpm) = a function of rpm which gives massflow of LN2 in (kg/s)
% massflow  = instantaneous mass flow  (kg/s)
```

```
% r = rolling friction coefficient from paramsd
% theta = angle in radians of the road (rad)
% slope70 =

% Load the operating parameters
paramsda;


trani3;
vdotd;
p_perf2;
pcurvea;

% Set the step size in seconds (s)
step = 1;                              % s

% Set the starting conditions
t(1) = time(1);
Rpm(1) = 0;
Tout(1) = 0;
a(1) = 0;
drag(1) = 0;
friction(1) = 0;
psiT(1) = 0;
tgtA(1) = 0;
massflow(1) = 0;
% speed(1) = 31;
v(1) = speed(1);
gear(1) = 3.45;
totalmdot = 0;
theta = 0;
i = 1;
mdotreq(1) = 0;

specwrk = 141.4;                              % kJ/kg
```

```
differential = 3.67/2;
diam = 0.6;                       % m   Wheel diameter - measured

while totalmdot <= N2             % Range on Tanks
% while v(i) < 8.9408             % 20 mph - for hill climb
% while v(i) < 13.41              % 30 mph
% while i < 1372                  % Whole City Cycle
% while i < 765                   % Whole Highway Cycle

    i = i + 1;                          % goes to next time step
    t(i) = time(i);                     % s
%
    mass = m_o-totalmdot;               % kg   Decreases mass of car as fuel is consumed
%   mass = m_o;                         % kg
%

% speed(i) = 13.41;               % 30 mph       Setting desired speed to accelerate to
% speed (i) = 8.9408;             % 20 mph
% speed(i) = 23.25;               % 52 mph
% speed(i) = 40;              % max out!

    % Now calculate current velocity using the acceleration calculated in the last step,
    % or the last speed desired, for braking:
       v(i) = v(i-1) + a(i-1)*(t(i)-t(i-1));    % m/s
    if v(i) < 0
       v(i) = 0;
    end;

    if v(i) > (speed(i-1) + 3)
       v(i) = speed (i-1);
    end;

    % What's my new target acceleration? (m/s^2) : [speed wanted - current speed] / delta time
    tgtA(i) = (speed(i) - v(i)) / (t(i) - t(i-1));          % m/s^2
```

```
% Calculate drag and rolling friction forces based on velocity and vehicle weight
   % Calculate the aerodynamic drag (N)
   drag(i) = 0.5*rho*Cd*area*v(i)^2;

   % Calculate the rolling resistance (N)
if v(i) < 0.1
   friction(i) = 0;
else
   friction(i) = r*(mass)*cos(theta)*g*(1 + 1e-3*v(i) + 1e-5*v(i)^2);
end;

%%%%%%%%%%%%%%%%%% Find Rpm %%%%%%%%%%%%%%%%%%%%%%
% What gear should I be in, based on current velocity, and finding gear which gives most available torque
% to wheels using gears from trani3,
   gr = [firstgear secondgear thirdgear fourthgear fifthgear];

   j = 0;
   while j < 5
      j = j+1;
      R(j) = (v(i)/(pi*diam))*60*gr(j)*differential;
      P(j) = polyval(pca,R(j)+1);                                           % kW
      wT(j) = P(j) * 60000/(2*pi*(R(j)+1)) * .85 * gr(j) * differential;    % Nm
   end;

   if wT(1) == max(wT)
      gear(i) = gr(1);
      Rpm(i) = R(1);
      Pwr(i) = P(1);                  % kW
      wheelTrq(i) = wT(1);            % Nm

   elseif wT(2) == max(wT)
      gear(i) = gr(2);
      Rpm(i) = R(2);
      Pwr(i) = P(2);                  % kW
```

```
    wheelTrq(i) = wT(2);                    % Nm

elseif wT(3) == max(wT)
    gear(i) = gr(3);
    Rpm(i) = R(3);
    Pwr(i) = P(3);                          % kW
    wheelTrq(i) = wT(3);                    % Nm

elseif wT(4) == max(wT)
    gear(i) = gr(4);
    Rpm(i) = R(4);
    Pwr(i) = P(4);                          % kW
    wheelTrq(i) = wT(4);                    % Nm

elseif wT(5) == max(wT)
    gear(i) = gr(5);
    Rpm(i) = R(5);
    Pwr(i) = P(5);                          % kW
    wheelTrq(i) = wT(5);                    % Nm
end;

% What amount of torque is required to get the target acceleration?
% Torque = ( (mass*accel) + drag + friction + weight*sin(theta) ) )*(wheel radius)/(gear ratios *
.85)  --> 0.85 for torque transmission inefficiencies

Treq(i)=((tgtA(i)*(mass))+drag(i)+friction(i)+mass*g*sin(theta))*(diam/2) / (gear(i) *differential*0.85);

% "Coasting" feature.
if tgtA(i) < 0                                  % Nm
    Treq(i) = 0;                            % Nm
end;

Preq(i) = Treq(i) * 2 * pi * (Rpm(i)+1) / 60000;        % kW

if Preq(i) <= 0
```

```
        Pwr(i) = 0;
      end;
      massflow(i) = Pwr(i) / specwrk;                    % kg/s

%%%%%%%%%%%%%%%%%% Acceleration Calc %%%%%%%%%%%%%%%%%%
      % What's my acceleration based on the torque output? (m/s^2)
      % Use T/(radius of tire) = Favailable   => measured diameter of car at .6 m
      % Also using a factor of 0.85 for inefficiencies in torque transmission
      % Circumference of gear depends on which gear you're in - again using trani3:
      Trq(i) = Pwr(i) * 60000 / (2 * pi * (Rpm(i)+.00001));   % Nm

      if Trq(i) > 450                                    % 80% of maximum (starting torque)
        Trq(i) = 450;                               % Nm
      end;
      wheelTrq(i) = Trq(i) * .85 * gear(i) * differential;      % Nm

      % What's my acceleration?
        a(i) = ( (wheelTrq(i)/(diam/2)) - drag(i) - friction(i) - mass*g*sin(theta)) / (mass);  % m/s

      % Calculate the total LN2 consumed so far
      totalmdot = trapz(t,massflow);                             % kg

%     if i > 45                                      % feature stops car after 45 seconds (hill-climb)
%        v(i) = 20;
      if i > 1372                                        % feature stops car at end of City Cycle
        totalmdot = 20000;
      end;
end;

totalmdot                            % (kg)
Totaltime = max(t)                   % (s)
Totalrange = trapz(t,v)/1000         % (km)
maxv = max(v)                        % (m/s)
```

```
figure(1);
clg;
plot(t,v*2.23,time,speed*2.23);
grid;
xlabel('time (s)');
ylabel('mph');
title('Velocity versus Time');
legend('Car Speed','Cycle Target');
```

PCURVEA.M

```
% This code figures out what the power and versus Rpm curve given a max power and rpm,
% using max power for the adiabatic case

%rpm = [0:1:2716];

% Calculate the power curve fit at 90 psi
POWER = [0 40 0];                    % Power (kW)
RPM = [0 1358 2716];
pca = polyfit(RPM,POWER,2);
```

Appendix C: Future Vehicle Simulation Code

PARAMSDF.M

```
% This is the parameter file for the driving cyle simulations.

precis = 0.001;

% Load the driving cycle
load ctyspeed;                              % Speed (mph)
speed = speed/2.237;                        % Speed (m/s)
load ctytime;                               % Time (s)

% Automobile parameters
P = (90) * 101320/14.7;                     % Operating pressure (Pa)
m_o = 1030;                                 % Starting mass (kg) original estimate: 1675 kg
area = 1.88;                                % Frontal area (m^2)
Cd = 0.4;                                   % Coefficient of drag
r = 0.013;                                  % Rolling resistance
n = 4;                                      % Number of LN2 Dewars in vehicle
N2 = n*(0.075)*nist(101325,77,'Density');   % Stored nitrogen (kg) (number of tanks)*(tank volume
m^3)*density of sat liq Nit at 350 psi

% Other parameters
rho = 1.226;                                % Density of air (kg/m^3)
g = 9.81;                                   % Gravity (m/s^2)
```

PCURVEF.M

```
% This code figures out what the power and versus Rpm curve given a max power and rpm,
% using max power for the adiabatic case

%rpm = [0:1:2716];

% Calculate the power curve fit at 90 psi
```

```
POWER = [0 30 0];                    % Power (kW)
RPM = [0 1358 2716];
pca = polyfit(RPM,POWER,2);
```

Most of this growth will occur in developing countries which have little or no emission controls.[1] According to the U.S. Environmental Protection Agency (EPA), more than half standards.[2] In urban areas of southern California, vehicles account for over 50% of the air pollution emitted.[3]

enacted the Low Emission Vehicle (LEV) program.[4] The LEV program established pollutants.[5] Similar mandates have also been adopted by New York and Massachusetts.

photovoltaic energy conversion[6]. General Motors' EV1, powered by electrochemical batteries.[7]

with about 10.1 MJ/kg for gasoline, assuming an overall thermal efficiency of 25%.[8] Lead lead is released into the environment during processing and manufacturing.[9] This leads to factors they felt were important in determining which vehicle to purchase. [10] Such factors vehicle, not as an environmental solution."[11] It is reasonable to assume the same argument operating a vehicle powered by liquid nitrogen.[12] Issues pertaining to frost-free heat s.[13] approximately 13 cents/mile to operate when battery replacement costs are included.[14] manganese.[15]

for absorbing energy during an impact.[16] Much is also known a margin of safety.[17] California's ZEV guidelines.[18] Other environmental automobiles.[19] The next section viable targets for CO_2 sequestration.[20] A modern ni CO_2.[21] This can in several ways the atmosphere.[22,23,24] This process raises the posid nitrogen- ast,[25,26] a limited amount has n.[27] to be used in. [28]s knowledge.[29]ith a boil-off rate of about 3% per day.[30] Theoperating pressure.[31] Transmission gear ratios used in the program are standard for the ual values. Aerodynamic drag is approximated by the following equation:[32]

aerodynamic effects.[33] The rolling resistance can be estimated using another simple (1070 RPM).[34] Th.[35] A large amount of gas is completely lost into the crankcase and simply more work must be done before even one will be on the highway.